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Experimental studies on gas and dust emissions to the atmosphere in rabbit and broiler buildings

Salvador Calvet Sanz

Supervisor: Prof. Dr. Antonio G. Torres Salvador
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Summary

Atmospheric pollution caused by the intensive rearing of farm animals affects the global environment, human health and the welfare of farm animals. This topic has aroused increasing interest in countries such as Spain, where little research has been done until recently. This doctoral thesis focuses on the experimental measurement of concentrations and emissions of gases (ammonia, methane, nitrous oxide and carbon dioxide) and particulate matter (PM_{10}) in broiler and rabbit farms, chiefly in Mediterranean climate conditions, and examines the different factors affecting these emissions. To fulfil these objectives, this thesis is composed of five different yet inter-related research studies. Firstly, the methodology followed to measure emissions is detailed. This methodology is based on a balance considering gas concentrations and ventilation flows. A procedure to analyse the uncertainty is proposed to obtain measurable indicators of the quality of the reported values. Secondly, the measurement of ventilation flows on commercial farms is described. This measurement consists of a circuit specifically designed to obtain and record information about the operation of the fans. Then, these two studies are applied to determine gas emissions in two commercial rabbit farms and one broiler facility in the Spanish Mediterranean coastal region. Finally, the influence of broiler activity on gas and particulate matter emissions is quantified in a study carried out in an experimental farm, and the applicability of an indirect method to determine ventilation flows in broiler farms based on a carbon dioxide balance was evaluated. The results obtained through these experiments and the subsequent analyses contribute to the general knowledge on gas emissions from broiler and rabbit farms, and they are highly useful to improve the national gas emission inventory.

Estudios experimentales sobre emisiones de gases y polvo a la atmósfera en alojamientos para conejos y pollos

Resumen

La contaminación atmosférica originada por la producción animal intensiva afecta al medio ambiente global, a la salud de las personas y al bienestar de los animales de la propia granja. Se trata de una problemática de creciente interés en países en los que, como en el caso de España, se ha investigado poco hasta el momento. Esta tesis doctoral se centra en la medición experimental de concentraciones y emisiones de gases (amoniaco, metano, óxido nitroso y dióxido de carbono) y partículas (PM_{10}) en granjas de pollos de cebo y de conejos, principalmente en clima mediterráneo, analizando los factores que afectan a dichas emisiones. Para ello, la tesis se compone de cinco trabajos de investigación diferenciados, aunque estrechamente relacionados entre sí. En primer lugar, se estudia en detalle la metodología empleada para medir las emisiones, basado en un balance en el que las variables son la concentración de gases y el flujo de ventilación; por otra parte, se desarrolla un procedimiento para el análisis de la incertidumbre cuyo objetivo es obtener indicadores de la calidad de los resultados. En segundo lugar, se aborda la medición del flujo de ventilación en granjas comerciales mediante el desarrollo de un circuito para la adquisición de información sobre el funcionamiento de los ventiladores. Posteriormente, y en aplicación de los dos anteriores estudios, se determinan las emisiones de gases en dos granjas comerciales de conejos y una de pollos en el litoral mediterráneo español, obteniendo resultados muy útiles para la mejora del inventario nacional de emisiones. Finalmente, se ha cuantificado la influencia de la actividad de los pollos de engorde en las emisiones de partículas y de gases, y se ha evaluado la aplicabilidad de un método para la determinación indirecta de la ventilación basado en el balance de dióxido de carbono. Los resultados obtenidos en estos experimentos y en los correspondientes análisis contribuyen al conocimiento general acerca de las emisiones de gases en granjas de pollos y conejos, y son muy útiles para mejorar los inventarios nacionales de emisión.

Estudis experimentals sobre emissions de gasos i pols a la atmosfera en allotjaments per a conills i pollastre

Resum

La contaminació atmosfèrica originada per la producció animal intensiva afecta el medi ambient global, la salut de les persones i el benestar dels animals a la pròpia granja. Es tracta d'un problema d'interés creixent en països en els quals, com és el cas d'Espanya, s'ha investigat poc fins ara. Esta tesi doctoral es centra en la medició experimental de concentracions i emissions de gasos (amoníac, metà, òxid nitrós i diòxid de carboni) i partícules materials (PM_{10}) en granges de pollastres d'engreix i de conills, principalment en clima mediterrani, analitzant els factors que afecten aquestes emissions. Per a complir estos objectius, la tesi es compon de cinc treballs d'investigació diferenciats, encara que estretament relacionats entre sí. Primerament s'estudia amb detall la metodologia utilitzada per a mesurar les emissions, basat en un balanç en el qual les variables són la concentració de gasos i el fluix de ventilació, i es desenrotlla un procediment per a l'anàlisi de la incertesa, l'objectiu del qual és obtindre indicadors de la qualitat dels resultats. En segon lloc, es tracta la medició del fluix de ventilació en granges comercials mitjançant el disseny d'un circuit per a la adquisició d'informació sobre el funcionament dels ventiladors. Posteriorment, i en aplicació dels dos anteriors estudis, s'han determinat les emissions de gasos en dos granges comercials de conills i una de pollastres en el litoral mediterrani espanyol, obtenint resultats molt útils per a la millora de l'inventari nacional d'emissions. Finalment, s'ha quantificat la influència de l'activitat dels pollastres d'engreix en les emissions de partícules i de gasos, i s'ha avaluat l'aplicabilitat d'un mètode per a la determinació indirecta de la ventilació basat en el balanç de diòxid de carboni. Els resultats obtinguts mitjançant estos estudis i les posteriors anàlisis contribueixen al coneixement general sobre emissions de gasos a les granges de pollastre i conills, i són aplicables per a millorar els inventaris nacionals d'emissions.

Doubt is not a pleasant condition,
but certainty is absurd.

(Voltaire)

Believe those who are seeking the
truth; doubt those who find it.

(André Gide)

To those who learnt me to read, to write and to count

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List of units and magnitudes

The following list contains the main units and magnitudes used in this thesis and in square brackets, if appropriate, the units which will be used in the document unless otherwise stated. For dimensionless magnitudes the symbol [-] will be used.

a	fan activity or proportion of the time that a fan is working [h·h^{-1}]
A	ampere
Ai	activity index: proportion of active birds at a certain time
C	gas concentration in general [mg·m^{-3}]
C_i	gas concentration inside a farm building [mg·m^{-3}]
C_{inlet}	inlet gas concentration [mg·m^{-3}]
C_{outlet}	outlet gas concentration [mg·m^{-3}]
d	day
D	fan diameter [m]
ΔC	change in gas concentration between two consecutive measurements in a balance [mg·m^{-3}]
ΔP	pressure drop in a farm building [Pa]
E	emission [mg·h^{-1}]
E_{CO2}	CO_2 emission in the carbon dioxide balance [L·animal^{-1}·h^{-1}]
ER_H	hourly emission rate [mg·animal^{-1}·h^{-1}]
ER_C	emission rate as cycle mean [mg·animal^{-1}·d^{-1}]
ER_D	emission rate as daily mean [mg·animal^{-1}·d^{-1}]
EF	emission factor [several units]
F_A	correction factor for animal activity used in the carbon balance method [-]
F_{CO2}	carbon dioxide production factor [L·W^{-1}]
F_E	heat production factor [W·kg$^{-0.75}$]

F_{litter}	proportion of the total carbon dioxide produced by litter in a building [-]
g	gram
h	hour
kg	kilogram
kW	kilowatts
LU	livestock unit
LW	live weight [kg]
m	metre
M	number of repetitions in the numerical propagation of uncertainty using Monte Carlo methods [-]
m_{CO2}	carbon dioxide mass flux for the carbon dioxide balance [$g \cdot h^{-1}$]
N	number of animal places [places]
ν	degrees of freedom [-]
P	air pressure [Pa]
Pa	pascal
PM_{10}	particles with aerodynamic equivalent diameter less than or equal to 10 μm [$mg \cdot m^{-3}$]
ppm	parts per million, or volume fraction of a gas in the air [-]
Q_N	nominal flux of a fan [$m^3 \cdot h^{-1}$]
Q_P	fan extraction capacity at a certain pressure drop [$m^3 \cdot h^{-1}$]
RH	relative humidity in air [-]
r_{ik}	correlation coefficient between the variables x_i and x_k
s	surface of the fan or exhaust area [m^2]
S	sink term in a mass balance [$mg \cdot h^{-1}$]
T	temperature [ºC]
TSP	total suspended particles [$mg \cdot m^{-3}$]

u_c	combined standard uncertainty
$u(x)_i$	standard uncertainty of a variable x_i
v	air velocity in an exhaust fan [m·s^{-1}]
V	ventilation flow [m^{3}·h^{-1}]
Vol	volume of the considered space in a mass balance [m^{3}]
W	Watt (metabolic energy produced per time unit)

List of terms and abbreviations

The following list contains the main abbreviations used in this thesis.

AC	alternating current
APAT	*Agenzia per la protezione dell'ambiente e per i servizi tecnici* (Italian Agency for Environment Protection and Technical Service).
ASABE	American Society of Agricultural and Biological Engineers
BAT	best available technique
CH_4	methane
CIGR	*Commission Internationale du Genie Rural* (International Commission of Agricultural Engineering)
CO_2	carbon dioxide
DC	direct current
DIAS	Danish Institute of Agricultural Sciences
DIN	*Deutsches Institut für Normung e.V.* (German Institute for Standardization)
ECETOC	European Centre for Ecotoxicology and Toxicology of Chemicals
EEA	European Environment Agency
EPER	European Pollutant Emission Register
EU	European Union
FIM	fan indication method
FOSVWE	*Forschungs- und Studienzentrum für Veredelungswirtschaft Weser-Ems* (Research Centre for Animal Production and Technology)
FRM	fan rotational method
FTIR	fourier transform infra red spectroscopy
GHG	greenhouse gases
HSE	Health and Safety Executive (UK)

IAST	Institute of Animal Science and Technology of the UPV
ICS	induction operated current switch
IPCC	International Panel on Climate Change
IPPC	Integrated Pollution Prevention and Control
ISO	International Organization for Standardization
JCGM	Joint Committee for Guides in Metrology
LRTAP	Long-Range Transboundary Air Pollution
MAPA	*Ministerio de Agricultura, Pesca y Alimentación* (Spanish Ministry of Agriculture, Fisheries and Food).
MCM	monte carlo methods
N_2O	nitrous oxide
NDIR	non-dispersive infra red spectroscopy
NH_3	ammonia
PAS	photoacoustic spectroscopy
PDF	probability density function
PID	passive infrared detector
RMS	residual mean square
TEOM	tapered-element oscillating microbalance
UK	United Kingdom
UN	United Nations
UN-ECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
UPV	Universidad Politécnica de Valencia
USA	United States of America

Chapter 1

Introduction, objectives and structure

1.1. Introduction

Animal husbandry, particularly the intensive rearing of livestock and poultry, causes environmental pollution to soil, water and atmosphere. However, atmospheric pollution has until very recently been considered less important than other types of contamination (water pollution or waste production), perhaps because its environmental effects are not so easy to comprehend, and because these pollutants cannot actually be seen. Animal production is a key source of gases, dust, odours, micro-organisms and noise in the atmosphere. All these emissions are relevant in three ways:

- Global effects. Some substances are responsible for long-range pollution and are subjected to international regulations. Methane (CH_4) and nitrous oxide (N_2O) are greenhouse gases (IPCC, 2007), while ammonia (NH_3) is crucial in relation to acidification and eutrophication (Krupa, 2003) and reduces atmospheric visibility because it is involved in the formation of aerosols (Barthelmie and Pryor, 1998).
- Human health and animal welfare on the farm. Air pollutants can reduce the air quality on the farm, affecting both workers and animals. Long-term exposure to dust and ammonia leads to chronic respiratory diseases (Roney *et al.*, 2004); noises can impair human and animal hearing; CH_4 accumulation in slurry tanks can cause asphyxia and certain infectious diseases can also be transmitted by air (Büscher *et al.*, 2005).
- Neighbourhood health and well-being. The emitted pollutants can negatively affect the quality of life in the neighbouring area. Odour production is the most common nuisance in the farm neighbourhood (Schiffman, 1998), and certain respiratory diseases are also more frequent among people living close to farms (Büscher *et al.*, 2005).

Air pollution from animal production has long been studied in Central and North European countries such as England, the Netherlands, Denmark and Germany. Over the last decade, numerous studies have also been conducted in the United States of America (USA). In Spain, however, this kind of studies has not been carried out until quite recently.

The research conducted for this thesis arises from a new research line initiated in 2001 in the Department of Animal Science at the *Universidad Politécnica de Valencia* (UPV) in Spain. A fundamental goal of this research line is to obtain relevant data on gas emission rates in Spanish conditions. A significant part of the work presented in this thesis was also carried out in the Research Centre for Animal Production and Technology (FOSVWE), in the Faculty of Agriculture at the *Georg-August-University of Göttingen* (Vechta, Germany).

1.2. Background

1.2.1. International commitments on gas emissions

Livestock production is subjected to international commitments on global pollution regarding greenhouse gas emissions (CH_4 and N_2O) and acidifying substances (NH_3). In both cases two tasks must be performed in order to achieve a reduction in the emissions:

- Estimation of yearly gas emissions by means of inventories, considering all activities responsible for said emissions.
- Establishment of mitigation techniques to reduce the emissions.

The emission inventories use two main parameters: first, activity data, which are the quantity of a pollutant activity in each country; and second, emission factors, which are average estimates of gas emission for each activity under specific conditions. The International Panel on Climate Change (IPCC) has proposed international default emission factors for greenhouse gases, but countries are strongly encouraged to use their own data (IPCC, 2001). Nevertheless, no data are available at the moment in Spain for any type of livestock production, and the Spanish inventory in this sector is therefore only a rough estimation.

International interest in greenhouse gas (GHG) emissions began in 1992 in the United Nations Framework Convention on Climate Change (UNFCCC), and took form in the Kyoto Protocol (UN, 1997), which established specific reduction objectives for 2010. Agriculture, particularly the livestock sector, is currently responsible for about 9% of the total GHG emissions in Europe (EU-27), and for Spain this relationship is estimated to be the same (EEA, 2007a).

The bases to reduce the emission of acidifying substances were established in the Geneva Convention on Long-Range Transboundary Air Pollution (UN-ECE, 1979). However, the international agreement to reduce NH_3 emissions was only established in 1999, in the Gothenburg Protocol to abate acidification, eutrophication and ground-level ozone (UN-ECE, 1999). The European Union (EU) adapted this protocol in the Directive 2001/81/EC (Ceilings Directive), limiting Spanish ammonia emissions to 353,000 tons by 2010. On average, the livestock sector makes up some 60% of all ammonia emissions (ECETOC, 1994), while agriculture contributes up to 90% (EEA, 2007b).

The limits for both ammonia and greenhouse gases in Spain are exceeded by 18% and 50%, respectively, according to the estimations reported in the national gas emission inventory in 2005 (EEA, 2007a; EEA, 2007b). More information about gas emissions under local conditions could greatly improve the quality of the inventories and reveal valid abatement techniques.

1.2.2. The integrated approach

Air pollution cannot be considered independent from soil and water pollution. An integrated approach is crucial to evaluate and minimise environmental impacts from animal production. This was the main objective of the 96/61/EC Directive on Integrated Pollution Prevention and Control (IPPC-Directive), which proposed the use of Best Available Techniques (BATs) considering environmental, technical and economic factors simultaneously. This Directive affects facilities for intensive poultry and pig production having more than 40,000 places for laying hens, more than 750 for sows or more than 2,000 for fattening pigs.

The "Reference Document on Best Available Techniques for Intensive Rearing of Poultry and Pigs" (known as BREF) summarises all available information on BATs for these two species (European Commission, 2003).

1.2.3. Absence of data for Spain

Due to the lack of information on emissions from Spanish animal production, the default emission factors proposed by the IPCC are used for greenhouse gas emission inventories (IPCC, 2001).

In the case of ammonia, North European experimental data on emissions from livestock production (ECETOC, 1994) have been adapted to Spanish livestock production by correcting the emissions depending on the temperature (Oldenburg, 1989) to produce well-documented semi-empirical calculations (MAPA, 2002). Nevertheless, these estimates have three main disadvantages. First, the data source is outdated and today there are better emission factor estimates. Second, the formula proposed by Oldenburg has a limited application and is unsuitable for predictions above 19ºC. Third, environmental temperatures should not be considered in some types of production such as poultry, because the environment is strictly controlled and it is therefore almost unaffected by outside conditions.

Furthermore, in some country-specific livestock productions only limited experimental data on gas emissions are available. As North European countries have traditionally provided gas emission estimates, the specific case of Spanish livestock production (*e.g.* rabbit production or pigs reared in the *dehesa* system) cannot be evaluated unless local studies are conducted.

Finally, the BREF document omits specific BATs for Spain due to the lack of information even though the Spanish livestock sector was involved in the writing of the document.

For all these reasons, measurements of emissions under local conditions are absolutely vital not only to allow Spain to fulfil international obligations, but also to effectively contribute to reducing farm pollution worldwide.

1.3. Measuring and reporting gas emissions

1.3.1. Measuring gas emissions in livestock buildings

There are four basic approaches to determine emission rates in livestock buildings (Phillips *et al.*, 2000):

- Feed and manure nitrogen balance.
- Summation of measured or modelled local sources.
- Determining gas fluxes in a control volume (gas balances).
- Tracer gas methods.

Whichever approach is chosen, gas concentrations and airflow rates must be measured, according to the following requirements (**Table 1.1**):

Table 1.1. *Requirements for measuring gas emissions*

Requirement	*Reason for this requirement*
Simultaneous measurement of NH_3, CH_4, CO_2 and N_2O	Need to conduct comprehensive analyses considering all atmospheric emissions
Measurements in commercial farms	Results close to real values
Spatial representation of the measurements	Gas concentrations show high spatial and temporal variability
Temporal representation of the measurements	Daily and yearly emission rates can vary considerably
Simultaneous measurement of gas concentration and ventilation rate	Necessary for determining emission rates
Report of environmental conditions	Quantification of influential parameters
Development of nutrient balances	Integrated approach as a global process
Standardized report of emission rates	Comparison with literature data and utility for further analysis
Hourly measurements	Determination of the daily effect
Repetition in different conditions	Distinction between summer and winter

Source: Translated by the author from Hartung *et al.* (2005).

1.3.2. Measuring ventilation rates

According to Phillips *et al.* (2001), two kinds of techniques are used in livestock buildings to measure ventilation rates. The first determines the ventilation rate indirectly by measuring a tracer parameter and applying a balance. The second is the direct determination of the ventilation rate by measuring airflow rates through all openings in a building and integrating them to obtain the overall ventilation rate. The latter technique is simpler, but can be applied only in mechanically-ventilated buildings.

1.3.3. Measuring gas concentrations

Different units are used to measure gases at low concentrations. The most commonly used is parts per million (ppm), which is rather a dimensionless volumetric proportion than a proper concentration unit (Seinfeld and Pandis, 1998). Gas concentrations can be also expressed as a mass fraction (*e.g.* $mg \cdot m^{-3}$ or $\mu g \cdot m^{-3}$). The relation between the two units can be obtained by means of the ideal gas law, and it is dependent on the temperature, atmospheric pressure and molecular weight of the considered gas. **Table 1.2** shows the equivalence between the two units under standard conditions.

Table 1.2. *Conversion of gas concentration units at 25°C and 101,300 Pa*

gas	1 ppm	1 mg·m^{-3}
NH_3	0.69 mg·m^{-3}	1.44 ppm
CH_4	0.65 mg·m^{-3}	1.53 ppm
N_2O	1.80 mg·m^{-3}	0.55 ppm
CO_2	1.80 mg·m^{-3}	0.55 ppm

Gas concentrations should preferably be expressed as a mass fraction, although the volumetric proportion is widely used in the literature. This recommendation meets two main objectives: International System units are used, and the calculation to obtain emission rates is easier.

The analytical techniques to determine gas concentrations in animal buildings must consider the requirements summarised in **Table 1.3.**

Table 1.3. *Requirements of the analytical techniques to determine gas concentrations in livestock buildings*

Criteria	*Requirements*		
Measurement range	NH_3:	0.1 – 100 ppm	0.07 – 70 mg·m^{-3}
	CH_4:	1 – 200 ppm	0.6 – 130 mg·m^{-3}
	N_2O:	0.3 – 10 ppm	0.55 – 18 mg·m^{-3}
	CO_2:	300 – 5,000 ppm	550 – 9,150 mg·m^{-3}
Resolution	At least 1% of the measured value		
Detection	At least background atmospheric concentration		
Selectivity	Compensation for cross effects		
Sampling	Avoid adsorption, diffusion and condensation during the sampling		
Time resolution	Hourly measurements, especially if the daily variation in gas concentrations is studied		
Calibration	Weekly control, and if necessary, zero adjustment and calibration		
Environment	Robust for long-term field measurements (dusty humid conditions)		

Source: Translated by the author from Hartung *et al.* (2005)

1.3.4. Reporting gas emissions

Gas emission in animal production must be reported as an **emission rate**, which according to Lacey *et al.* (2003: 1203) is "an expression of mass emitted per unit time, usually put in terms of production unit". However, in animal production, the emission is highly dependent on environmental and managing conditions (temperature, litter moisture, manure pH, ventilation rate, etc). Therefore, an emission rate must describe precisely the mass emitted (*e.g.* kg of NH_3), in a given activity (*e.g.* broiler production), and under highly specific environmental and rearing conditions.

Emission rates may be reported in two ways:

- Mass per animal place and unit time (*e.g.* kg $gas \cdot place^{-1} \cdot day^{-1}$). This basis is easy to understand and apply since the number of places is known in production statistics.
- Mass per weight and unit time (*e.g.* kg $gas \cdot h^{-1} \cdot kg^{-1}$ live weight). Although more difficult to report with precision, this calculation allows for a better comparison of results, especially when animals of different ages, weights, or even different types of animals, are compared.

An **emission factor** is a "representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant" (Lacey *et al.*, 2003: 1203). The emission factor is expressed as mass emitted per production unit, normally on a yearly basis. An emission factor is therefore an average value attempting to define the average emission of a relatively homogeneous activity (*e.g.* broiler production), in a geographical region (*e.g.* Spain), regardless of local climate variations (*i.e.* as a yearly average).

Like emission rates, emission factors may also be reported in two ways:

- Mass per place and year (*e.g.* kg $gas \cdot place^{-1} \cdot year^{-1}$). This basis is preferred in emission inventories since animal places are usually specified values in national statistics.
- Mass per weight and year (*e.g.* kg $gas \cdot h^{-1} \cdot kg^{-1}$ live weight). These units are not very useful for emission inventories, but they are valuable when comparing emissions from different animal types and when evaluating mitigation techniques.

In the research conducted in this thesis, both emission rates and emission factors will be reported in the different possible ways, so as to facilitate the comprehension of the results as well as further comparisons.

1.4. Research objectives and thesis structure

Five objectives were established for this thesis, in relation to atmospheric emissions (NH_3, CO_2, CH_4, N_2O and dust) from fattening poultry and rabbit facilities:

1) To describe techniques used to measure gas emissions in livestock buildings and to analyse the obtained data.
2) To calculate ventilation rates in mechanically-ventilated farms.
3) To develop and apply methods to measure gas and dust emission rates.
4) To identify the effects of environmental conditions on gas and dust emissions (especially in the Mediterranean climate).
5) To establish preliminary emission factors for rabbit and broiler production under local conditions in Spain.

To describe the research and report the findings related to these objectives, this thesis is divided in seven chapters, including one introductory chapter and the final conclusions. The chapters are structured as separate articles, each with specific objectives, materials and methods, results, discussion and bibliography. Even though this thesis is presented in separate articles, the research was conducted as a single coherent project, as follows.

The introduction (this chapter), contains a justification for the research, a description of the situation in Spain and definitions of concepts which are fundamental to this study. The general objectives and structure of this thesis are here described.

After this brief introduction, the methodological approaches to measure gas emissions and to analyse the obtained data are specified in chapter two. The mass balance method is detailed, since it is the main method used in this research. This method is based on the simultaneous measurement of ventilation rates and gas concentrations. Special emphasis is also given to the statistical analysis of the data, which is a crucial matter, yet sometimes absent in the literature on gas emissions. The uncertainty analysis using numerical methods is proposed as a suitable method to estimate the quality of the results.

The third chapter is related to the second overall objective and deals with the estimation of ventilation rates in commercial farms, as a preliminary step to apply the mass balance method previously described. The specific case of a broiler farm is presented, although the procedure was also used in the other farms studied for this research. The method consisted of a circuit that measured the time each fan on the farm is in operation. The characteristic curve of each fan was obtained as well. The uncertainty in the values of ventilation rates was estimated as a previous step to obtain the uncertainty in the emission estimates, using the procedure described in chapter two.

The fourth and fifth chapters report findings from the experiments on gas emissions and the nitrogen cycle in rabbit and broiler farms, respectively, using the mass balance method described in the second chapter and the measurement system for ventilation rates as described in chapter three. The experiments were conducted in 2006 and 2007 in commercial farms located in the region of Valencia. In these two chapters, the effects of animal age, ventilation rate and the litter properties are analysed. Although not explicitly measured in these two chapters, animal activity is highlighted as a possible factor affecting atmospheric emissions, and therefore this parameter was further studied for broilers in the sixth chapter.

The sixth chapter analyses the measurement of gas and dust emissions in terms of the lighting programme and animal behaviour. The experiment was carried out on an experimental broiler farm in the FOSVWE (Vechta, Germany). Animal activity was determined by direct observations of video recordings, and was related to gas and dust production. The production of gases was compared to the results obtained in the Spanish commercial farms described in chapter five. In this chapter, an indirect method to determine ventilation flows based on the carbon dioxide balance is also tested as compared to direct measurements of ventilation flows. This indirect method can be considered suitable for measuring ventilation rates in mechanically-ventilated buildings and it is perhaps the most reliable method in naturally-ventilated farms.

Finally, chapter seven aims to provide a coherent and integrated perspective of the research as a whole. In this chapter the most noteworthy results are summarised, and the specific contributions of the research are highlighted, together with their implications for the reduction of environmental pollutants, as well as for the health and well-being of animals and labourers. Finally, ongoing studies arising from this research and possible objectives for future studies are enumerated.

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Chapter 2

Uncertainty analysis in experimental gas emission estimates

Uncertainty analysis in experimental gas emission estimates

Abstract

Gas emissions from livestock buildings have generally been measured using a gas balance in the whole building. However, the analysis of the data obtained can, in many cases, be more comprehensive than what is usually reported in the literature: sometimes, only the average values are specified; more commonly, standard deviations of the measured values are included. In some cases, more complicated statistical models are used to relate the measured emission to the influential variables. The aim of this chapter is to apply the uncertainty analysis as a technique to evaluate the quality of gas emission estimates. This technique consists in quantifying all uncertainty sources involved in the measurement system, and combining them in order to obtain a parameter associated with the result of the measurement which indicates the quality of the measurement. Two approaches were compared in order to calculate the combined uncertainty: one analytical method based on the first-order Taylor series and a numerical method to propagate probability density functions based on Monte Carlo techniques. Both methods resulted to be equivalent in most cases, although the Monte Carlo method performed better with correlated magnitudes and with non-normal distributions. In this study, the annual emission rates of ammonia in a broiler farm and the corresponding uncertainties are determined and reported herein. The gas concentration was identified as the major source of uncertainty in a single emission measurement, whereas the ventilation rate was the main source when the total emission in a cycle was considered.

Keywords: gas balance, gas emissions, ammonia, uncertainty analysis, Monte Carlo.

2.1. Introduction

2.1.1. Measuring gas emissions using air mass balances

As a gas pollutant source, livestock production is complex in comparison to other sources, because of the varied physical, chemical and biological aspects involved in the emission process. Furthermore, in certain cases the source is difficult to identify, since the animals, the manure and the dirty surfaces are gas sources with varied characteristics: point or area sources, which can be stationary or mobile. These aspects must all be considered when measuring gas emissions from livestock production.

Phillips *et al.* (2000) defined four basic approaches to determine gas emission rates in livestock buildings facilities:

- Feed and manure nutrient balances.
- Summation of measured or modelled local sources.
- Determining gas fluxes in a control volume (gas balances).
- Tracer gas methods.

The mass balance determining gas fluxes in a control volume is a widely used technique in research (see Wathes *et al.*, 1998), since the whole building can easily be used as a control envelope. The balance must consider all sources and sinks inside the building.

A double interpretation of the emission process is possible in animal buildings. First, the emission from a building to the atmosphere is a process closely related to the ventilation flow, and it can be evaluated regardless of the internal source (**Figure 2.1**.a). The gas emission balance from a building to the atmosphere is calculated according to the following equation:

$$E = \left(C_{outlet} - C_{inlet}\right) \cdot V \qquad \textit{(Equation 2.1)}$$

Where:

E: Emission to the atmosphere ($mg \cdot h^{-1}$)

C: Inlet and outlet gas concentration ($mg \cdot m^{-3}$)

V: Ventilation flow in the building ($m^3 \cdot h^{-1}$)

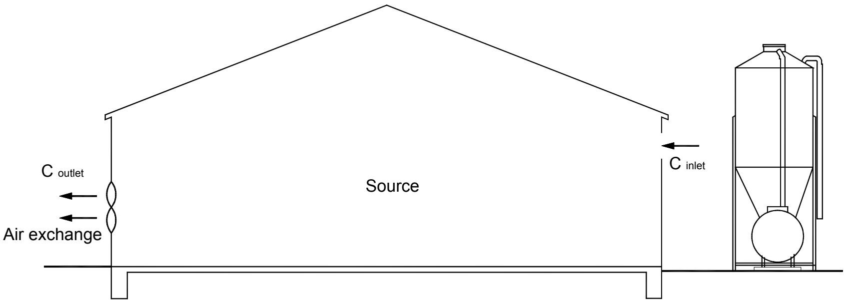
The second interpretation is based on the emission process and depends on physical, chemical and biological factors, whereas ventilation flow only affects the way in which the pollutant is extracted to the atmosphere (**Figure 2.1**.b). In this case, the balance considers all sources and sinks inside the building, and the balance equation is more complicated and is expressed as follows:

$$C_{inlet}\cdot V+E=C_{outlet}\cdot V+Vol\cdot\Delta C+S \qquad \text{(Equation 2.2)}$$

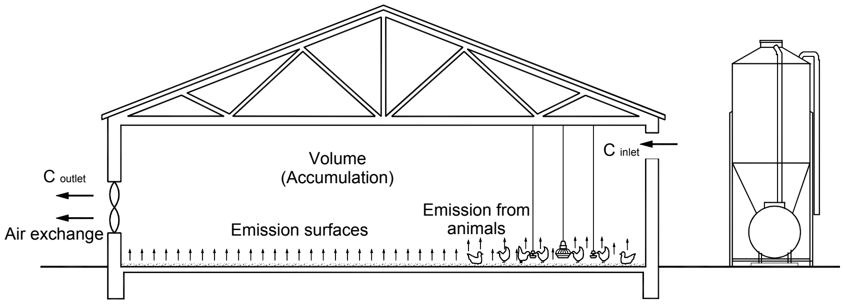
In this equation other terms are also considered:

S: Pollutant sinks in the building ($mg\cdot h^{-1}$)

Vol x *ΔC:* Accumulation in the building ($mg\cdot h^{-1}$)



a) Atmospheric emission approach



b) Emission process approach

Figure 2.1. *The two basic approaches for emission estimates: a) Emission approach without considering the internal sources; b) Process approach in which internal sources are considered*

In this expression, the emission term E is not the emission to the atmosphere, but rather the amount of pollutant released to the internal air of the building according to physical laws (*e.g.* ammonia volatilization from manure) or biological processes (*e.g.* carbon dioxide from animal respiration). Atmospheric pollutant sinks in the building include adsorption (*e.g.* ammonia), deposition (*e.g.* dust) or reaction (*e.g.* ammonia) of the considered pollutant, whereas the accumulation term is determined by the change in the concentration ΔC between two consecutive measurements.

Under many practical operating conditions, ventilation flow is quite high in relation to the control volume, and short-term variation in concentration values is small in relation to the other terms of the balance; in these cases the accumulation term $Vol \times \Delta C$ may be negligible. The term S is also negligible for the gases usually measured on farms, but it may be crucial when studying other pollutants such as dust or microorganisms.

In practice, and considering the simplified conditions for the terms S and $Vol \times \Delta C$ explained above, Equations 2.1 and 2.2 are equivalent for measuring gas emission rates; the obtained emission rate is therefore an estimate of both the emission from the building to the atmosphere and the chemical process of gas production inside the building.

2.1.2. The quality of the measured data

Data for emission estimates are normally analysed as follows. First, the rough data are screened for incorrect values caused by instrumentation failure. Second, an exploratory data analysis is performed including central and dispersion estimates (*i.e.* means and standard deviations or variances). Finally, further analyses can be performed to determine correlations between variables or analysis of variance, for example.

However, the determination of an emission rate must include not only the final value, but also an estimation of the quality of this value. This is crucial for two reasons. On the one hand, scientists and engineers can understand and make better use of the results of a study. On the other hand, policy makers must understand the credibility of the data in order to make sound policy decisions (Boriack *et al.*, 2004). Considering that errors in determining ventilation flows are normally over 10% of the measured value (Casey *et al.*, 2002), and that the measured concentrations are very often near the threshold of most instrumental devices, it may be concluded that errors in emission estimates are high.

One method of showing the reliability of data is by reporting uncertainty, which is defined as “a parameter associated with the result of a measurement, that characterises the dispersion of the values that could reasonably be attributed to the measurand” (ISO, 1995:2), and which can be reported in two ways: a standard deviation, and a credibility interval, containing the true value for a given confidence level (Ellison *et al.*, 2000). Uncertainty can be measured by statistical methods (Type A uncertainty) or by other means using prior knowledge (Type B uncertainty) which are not less accurate than Type A analyses, and can include expert judgement and calculated uncertainty by means of the law of propagation of uncertainty.

Uncertainty and error are related concepts which must not be confused. An error is defined as the difference between an individual result and the true value of the measurand. Errors cannot be exactly known, and three types of errors exist (Ellison *et al.*, 2000). First, random errors arise from unpredictable variations of a quantity measured, and the statistical distribution of these errors results in the uncertainty value. Second, systematic errors are defined as the difference between the averages obtained from an infinite number of replicated measurements of a given measurand and its (unknown) true value (ISO, 2004). These errors must theoretically be corrected, as far as they are known and quantified. The third type includes spurious errors, which normally invalidate a measurement and typically arise through instrument malfunction or human failure.

An error refers to a single measurement, whereas the uncertainty is related to a whole measuring system. Therefore, a measuring system may have a large uncertainty, yet a particular measurement with the system may have a small error due to random choice.

There is a general lack of information about the quality of the reported data in experimental research on gas emissions. Average values are normally reported, and sometimes the variability of the data is considered reporting the range of the measured values or the standard deviation of the mean. In general, there is however little information about the sources of errors and the credibility of the reported values.

Uncertainty in emission estimates may be attributed to three main causes (EPA, 1996):

1. The inherent variability in the process producing the emissions, as affected by environmental conditions in a complex way, results in a sampling uncertainty.
2. The measurement methods and instruments themselves have uncertainty in their results (parameter uncertainty).
3. The models used to perform the estimates are normally simplistic approaches of real processes, and therefore have uncertainties due to assumptions.

The main sources of uncertainty when calculating gas emission estimates are summarised in **Table 2.1**.

Table 2.1. *Uncertainty sources in gas emission estimates*

Cause	*Uncertainty source*	*Explanation*
Variability	Spatial variability	Variability between buildings and between parts of the building
	Temporal variability	Daily and yearly variations as affected by environment and animal type and age
	Other variability	Variation of the different variables over time: ageing of fans, changes in management schedules, etc.
Parameter uncertainty	Measurement	Inherent random error in measurement equipment
	Sampling	Sampling error as affected by sample size, sampling design and variability of the target population
	Systematic errors	Improper calibration of measurement systems; inherent bias in sampling procedure
Model uncertainty	Simplification	Use of a simplified model (*e.g.* a mass balance)
	Surrogate variables	Assumption of values for variables which are not measured

Source: adapted from EPA (1996)

2.1.3. Objectives

The first specific research objective of this chapter is to develop a general procedure to quantify uncertainty in measured gas emissions using the mass balance method on a farm. This general procedure will be used in the following chapters to analyse the specific results, and uncertainty values will be reported as an estimation of the quality of the obtained data.

The second objective is to quantify the contribution of each input variable to the final uncertainty. This is crucial to later propose improvements in the measurement system.

Special effort has been made in this thesis to implement numerical methods to estimate gas emissions, as explicitly recommended in the uncertainty evaluation in national greenhouse gas emissions inventories (IPCC, 2001).

According to ISO (1995), the analysis of uncertainty must fulfil three fundamental conditions: it must be universal, internally consistent and transferable. A method fulfilling these three conditions will therefore be used.

2.2. Methodology

2.2.1. General overview

A general case, attempting to obtain an annual ammonia emission factor in a broiler farm, is described in this chapter in order to illustrate the uncertainty analysis. Other situations (*e.g.* daily emission rates or gas emissions per animal produced) are simplifications of this general case.

The uncertainty in the estimation of emission rates was calculated according to three main steps: formulation, propagation and summarizing (JCGM, 2006).

2.2.2. Case study

The experiment layout is as follows: gas concentrations and ventilation rates are measured every two hours for a whole fattening cycle (48 days) in a commercial broiler farm (21,000 places) located in Villareal (Castellón) in summer conditions (July - August 2006). Between two consecutive cycles, a sanitation period (15 days) is customary for muck removal and disinfection of the buildings. Ammonia concentration was measured every two hours using a photoacoustic gas monitor, considering six measurement points (two external and four internal), and totalling 588 measurements for each measurement point. More details of this case study are explained in chapter 5.

Ventilation flows were determined directly, using a calibration curve of each fan relating the fan flux to the pressure drop. Details on the measurement of ventilation rates and the calculation of their associated uncertainties are further discussed in chapter 3.

2.2.3. Uncertainty evaluation

Uncertainty evaluation is considered a process by which a function gives an output quantity (the uncertainty of the measurand) using certain input quantities (the uncertainties of the variables on which it depends). The three main stages of this process are formulation, propagation and summarizing (JCGM, 2006), and were considered in this study as follows.

In the **formulation stage**, the first task was to clearly and unambiguously define what was being measured (the measurand), and then to determine the variables on which it depended. Next, a function relating the measurand to the variables $y = f(x_1, x_2 ...)$ was developed, and finally, on the basis of available knowledge, the corresponding probability density functions (joint PDFs) were assigned to each variable, considering correlations among them.

To assign a PDF to each variable, general recommendations made by ISO (1995), JCGM (2006) and Cox and Harris (2006) were followed. If errors are normally distributed and very accurate information about the variable is available, a Gaussian distribution $N(\mu,\sigma)$ can be adopted. A shifted and scaled t-distribution is recommended when the measurement is based on a reduced number of measurements. Finally, a rectangular distribution $R(a,b)$ must be used if the only available information is a lower limit a and an upper limit b (which is usual in data provided by manufacturers), according to the principle of maximum entropy introduced by Jaynes (1957).

In the **propagation stage**, the PDFs of the input quantities were propagated through the model to obtain the PDF of the measurand. Two approaches were considered: the law of propagation of the uncertainty, based on the first order Taylor series, and the propagation of distributions using analytical or numerical methods. Both methods are outlined in **Figure 2.2** and described in the following section.

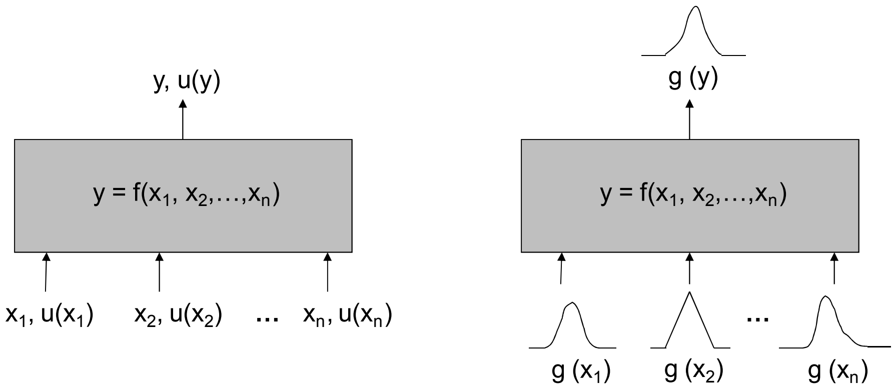


Figure 2.2. *Illustration of the propagation of the uncertainty. The law of the propagation of the uncertainty (left) and propagation of distributions (right). Source: adapted from JCGM (2006)*

Finally, in the **summarizing stage**, the value of the measurand, the associated standard uncertainty and a coverage interval (or credibility interval) for a stated coverage probability were obtained and reported. Furthermore, the relative contributions of all input variables were reported, as explained in section 2.2.4.

When the distributions are propagated, any statistical information relating to the measurand can be produced from the resulting PDF. However, when the law of the propagation of the uncertainty is used, only information on combined uncertainty is calculable.

Apart from the results, a complete report of a measurement result should include the following information as well, according to Ellison *et al.* (2000):

- Information about the formulation stage: the model used, the assumed distributions for each input variable and a full documentation on how each was evaluated.
- Information about the propagation stage: method used, correlations taken into account.

The data and analysis should be presented in such a way that the main steps can be readily followed and repeated, if necessary.

2.2.4. Two approaches to propagate uncertainties

In these experiments two approaches were considered and evaluated in order to determine uncertainty in gas emissions.

The **law of propagation of the uncertainty** (Equation 2.3) is based on a first-order Taylor series approximation of $y = f(x_1, x_2 \ldots)$ and combines individual standard uncertainties and covariances between variables according to the given equation relating the target measurand with the measured variables, in order to obtain the combined uncertainty (ISO, 1995).

$$u_c\left[y\left(x_1, x_2 \ldots\right)\right] = \sqrt{\sum_{i=1}^{n} c_i^2 \cdot u\left(x_i\right)^2 + \sum_{\substack{i,k=1,n \\ i \neq k}} c_i \cdot c_k \cdot u\left(x_i, x_k\right)} \qquad \text{(Equation 2.3)}$$

Where:

u_c	combined uncertainty
$y(x_1, x_2, \ldots)$	function with several input variables x_i
c_i	sensitivity coefficient, being $c_i = \delta y / \delta x_i$
$u(x_i)$	uncertainty of the input variable x_i
$u(x_i, x_k)$	covariance between x_i and x_k; $u(x_i, x_k) = u(x_i) \cdot u(x_k) \cdot r_{ik}$
r_{ik}	correlation coefficient between x_i and x_k

To use this equation all uncertainties must be expressed as standard deviations and the correlations must be known (Taylor and Kuyatt, 1994). Furthermore, if nonlinearity of $y = f(x_1, x_2 \ldots)$ is significant, higher-order terms in the Taylor series expansion must be included in the expression for u_c. Finally, the effective degrees of freedom for y must be estimated using the approximate Welch-Satterthwaite formula (ISO, 1995).

$$\nu_{eff} = \frac{u_c^4(y)}{\sum \frac{u_i^4(x_i)}{\nu_i}} \qquad \text{(Equation 2.4)}$$

Where ν_{eff} are the effective degrees of freedom; ν_i are the degrees of freedom for each variable, and u_i are the corresponding uncertainties.

The assumed distribution for y is then a shifted and scaled t-distribution having ν_{eff} degrees of freedom according to Equation 2.5, which approximates a normal distribution if there are many degrees of freedom (*e.g.* more than 50).

$$y = \bar{y} + t_{\alpha}(\nu_{eff}) \cdot u_c(y) \qquad \textit{(Equation 2.5)}$$

The **propagation of distributions** can be made analytically or numerically. The analytical combination of distributions is the only exact method to propagate uncertainties (Cox and Harris, 2006), but it can be applied only in relatively simple cases (*e.g.* linear models with only Gaussian distributions), and therefore it is not used in practice.

The Monte Carlo methods (MCM) provide a general approach to obtain an approximate numerical representation of the PDF of the measurand (JCGM, 2006). MCM perform random sampling from given probability distributions of the variables x_i, and evaluate the result y in each case. When this process is repeated many times (M repetitions), a numerical approximation of the PDF of y is constructed, and any property such as expectation, variance and coverage intervals can be approximated from it.

The software used to carry out these analyses was RiskAMP Monte Carlo Add-In Library version 2.70 for Excel (Structured Data, 2005), taking $M = 10^5$ repetitions. For each repetition the software remembers the result of the function, reporting the target information as a final result: mean value, standard deviation, and coverage intervals, obtained from the PDF obtained from the global simulation.

The relative contributions of the input variables to the combined uncertainty were numerically calculated according to Cox and Harris (2006: 166). For each input variable x_k the whole MC simulation was repeated holding all other input quantities at their central estimates. In this setting the model effectively becomes one having a single input quantity (x_k), and the uncertainty of the resulting distribution $u_k(y)$ is considered an approximation to the component of the combined standard uncertainty corresponding to x_k, and can be represented in relative terms to the total uncertainty $u(y)$ as follows.

$$Contribution\,(x_k) = \left(\frac{u_k(y)}{u(y)} \right)^2 \qquad \textit{(Equation 2.6)}$$

2.3. Results and discussion

2.3.1. Formulation stage

The measured variable is the annual emission rate, interpreted as the extrapolation of the measurement period to the whole year. Equation 2.7 is based on Equation 2.1 and describes the calculation of an annual emission rate in the case under study.

$$ER_Y = \frac{\sum_{day1}^{day48}\left(\sum_{hour1}^{hour24}\left(\left(C_{outlet} - C_{inlet}\right)\times V\right)\right)}{N} \times \frac{365}{D_{cycle} + D_{empty}} \qquad \text{(Equation 2.7)}$$

Where

ER_Y: Annual emission rate ($mg\cdot place^{-1}\cdot year^{-1}$)

C: Gas concentration ($mg\cdot m^{-3}$) in the inlet (C_{inlet}) and outlet (C_{outlet})

V: Ventilation flow in the building ($m^3\cdot h^{-1}$)

N: Number of animal places

D_{cycle}: Duration of the rearing period

D_{empty}: Duration of the sanitation period

The **Figure 2.3** shows a cause and effect diagram of the calculation. In this diagram, the process to obtain the annual emission rate is clearly defined, and the main uncertainty sources are identified. The ventilation rate is here considered an input variable, but this variable will be analysed and discussed in more detail in chapter 3.

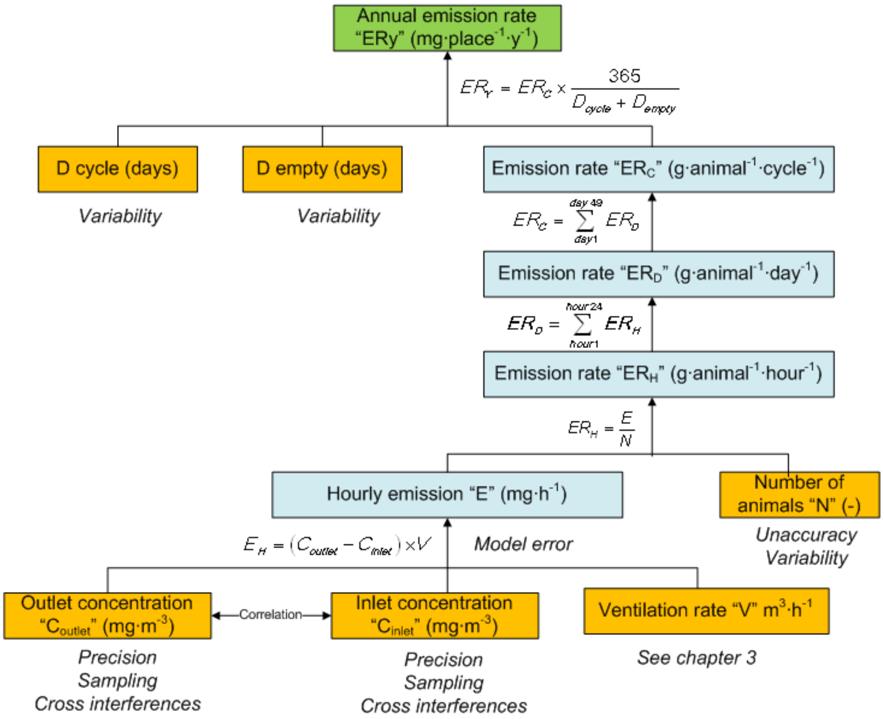


Figure 2.3. *Uncertainty cause and effect diagram. Orange titles represent the input variables, with their associated uncertainty sources. The green title is the target measurand. Blue titles are intermediate variables.*

A PDF was assigned to each uncertainty source, as follows.

The measurement of gas concentrations has two main types of uncertainty associated. First, the precision of the measurement depends on the measuring device itself, and is quantified in the calibration of the instrument. Second, there is always a sampling uncertainty, caused by temporal and spatial variations of gas concentrations. These two components relate to the ability to measure what has actually to be measured (concentrations of incoming and exhaust air) and were statistically determined by means of an analysis of variance using the *Proc GLM* of SAS System® (SAS, 2001) to evaluate the following model.

$$C_{ijk} = \mu + M_i + L_j + M_i \times L_j + \varepsilon_{ijk} \qquad \text{(Equation 2.8)}$$

Where:

C_{ijk}: Gas concentration in hour *i*, in the location *j*, and repetition *k*

M_i: Number of measurement ($i = 1; 2; ...; 625$)

L_j: Location (*j* = inlet; middle, outlet)

$M_i x L_j$: Interaction between measurement sample and location

ε_{ijk}: Model error

This model assumes constant variance for different values of measured concentrations. The results of this model are shown in **Table 2.2**. As expected, all considered factors were significative. The residual mean square (RMS) is the estimation of the variance not defined by the model, and therefore, its square root is an estimation of the uncertainty of the measuring system. In this case, $RMS = 0.45$ and therefore $u(NH_3) = 0.67$.

Table 2.2. *Analysis of variance of measured ammonia concentrations*

Source	Degrees of freedom	Sum of squares	Mean square	P>F
Total	4,964	22,392		
Model	1,861	20,998	11.3	<0.001
M	*624*	*12,615*	*20.2*	*<0.001*
L	*2*	*4,307*	*2,153*	*<0.001*
MxL	*1,235*	*4,076*	*3,30*	*<0.001*
Residual	3,103	1,394	0.45	

However, this approach is only valid if the variance of measurements is independent from the measured value.

In order to test the assumption of constant variance, a linear regression was used to compare the residual squares for each measurement (ε_{ij}) against the measured values C_{ij}. As shown in **Figure 2.4**, a positive relation was found, and therefore the hypothesis of uniform variance was rejected, using the numerical relationship in **Figure 2.4** to estimate the corresponding uncertainty.

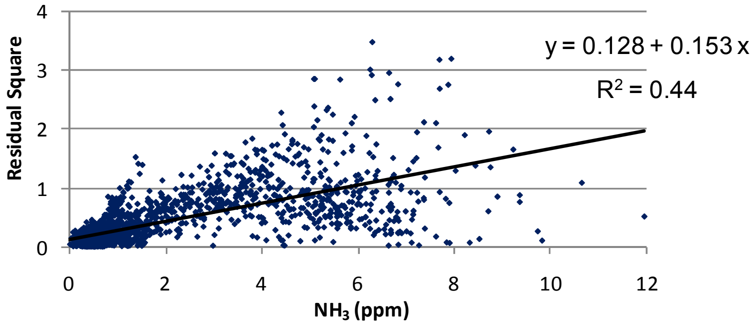


Figure 2.4. Linear relationship between the measured concentration and the residual squares of the measurements

The PDF of a single concentration measurement is calculated according to a normal distribution (see **Table 2.3**), where the mean value is the average of the corresponding measured concentration and the variance is the RMS, divided by the number of repetitions for each measurement (N_M = 2 if j=*inlet* and N_M = 4 if j=*outlet*).

There is also a third source of uncertainty caused by corrections for cross interferences, because the photo-acoustic gas monitor corrects cross interferences between methane and water vapour, and between carbon dioxide and nitrous oxide. These interferences and the corrections to be applied are obtained in the calibration of the instrument.

The number of animal places has two uncertainty sources. First, imprecision arises from the inability to know the exact number of live animals at a given moment in a large commercial broiler farm. The second uncertainty source is the variability between cycles caused by differences in initial populations or mortality. The first term may be negligible because animals were daily controlled. The second term relating to variability is obtained according to the farm records over the last five years, resulting in a normal distribution with a mean value of 21,000 animals in summer conditions with a standard deviation of 300.

Uncertainty associated to the determination of the length of the cycle and sanitation period is related to the variability between cycles. The best estimate of this variability in a commercial farm was found to be the revision of the farm records over the last years, resulting in a normal distribution with average 48 days for the fattening period and 15 days for the sanitation and cleaning period, with a standard deviation of 3 and 2 days, respectively.

The model uncertainty referred to the physical validity of Equation 2.1 is zero, because this model is not an approximation of the reality but the reality itself: Equation 2.1 gives by definition the emission rate of a building. Finally, the uncertainty associated to the ventilation flow in poultry farms is a more complicated task that will be addressed in chapter 3. **Table 2.3** shows the explanation and treatment of each uncertainty source and summarises the data presented above.

Table 2.3. *Uncertainty sources and quantification in the determination of the annual emission rate in a poultry farm according to the described methodology*

Variable	*Uncertainty source*	*Quantification*	*PDF*
C_{outlet} C_{inlet}	Instrument precision and sampling	ANOVA of measurements	$N\left(\bar{x}_i;\frac{RMS}{N_M}\right)$
	Cross interferences	Instrument calibration	Rectangular
Number of animal places	Imprecision	Negligible because of daily supervision	-
	Variability	Revision of farm records over the last five years	*N (21,000; 300)*
D_{cycle} D_{empty}	Variability	Revision of farm records over the last five years	*N (48;3)* *N (15;2)*
Model	Physical validity	Zero (by definition)	-
Vent. flow	See chapter 3	See chapter 3	

Correlations between inlet and outlet concentration measurements exist, since the same instrumental method was used in the two cases, and inlet concentration is physically included in the outlet concentration. This correlation was evaluated with the correlation coefficient between the measured data, using the *Proc Corr* of SAS System® (SAS, 2001). It was assumed that no correlation exists between any of the other variables.

2.3.2. Propagation stage

The law of propagation of the uncertainty could only be used until obtaining the hourly emission rate ER_h, because all uncertainties and correlations were clearly identified and quantified until this step. At this point, correlations between the different values of ER_h could not be considered with this method. For this reason, the propagation of PDFs based on numerical methods (MCM) was used.

The software RiskAMP Monte Carlo Add-In Library version 2.70 used random values from the given PDFs defining the input variables, and the results (mean, standard deviation and coverage interval) were obtained from the resulting PDF for y.

The correlations were taken into account as follows:

a) For correlated values (*e.g.* inlet and outlet concentrations) the RiskAmp function *correlatednormalvalue* was used.

b) For correlations derived from one measured parameter taking part in several parts of the calculation (*e.g.* the ventilation rate), the same simulated value was used, and therefore the derived correlation was automatically considered.

There are five main restrictions limiting the use of the law of propagation of the uncertainty (Cox and Harris, 2006). First, the non-linearity of y must be insignificant, and otherwise higher-order terms of the Taylor series must be added. Second, y can only be represented by a Gaussian distribution or a shifted and scaled t-distribution. Third, the standard uncertainties of all variables x_i must contribute in comparable terms to the combined uncertainty. Fourth, the value of the uncertainty must be small in comparison to the value. And fifth, the degrees of freedom of y must be calculated using the questioned Welch-Satterthwaite formula (Ballico, 2000; Hall and Willink, 2001).

MCM are much more versatile than the uncertainty propagation formula because they have none of the restrictions cited above. Even with relatively few iterations (*e.g.* $M = 10^3$) expectations and standard deviations can be accurately obtained. To calculate coverage intervals more iterations are needed (*e.g.* $M = 10^5$) because the distribution tails must be properly represented in the random sampling. Although MCM are computationally labour-intensive, the calculation times taken are often only seconds or minutes on a PC, unless the model is very complicated (Cox and Harris, 2006).

2.3.3. Summarizing stage

The value of the measurand, the associated standard uncertainty and a coverage interval (or credibility interval) for a stated coverage probability were reported. All information involved in the estimation of the uncertainty (*e.g.* input variables, model relating the input variables to the measurand and assumed PDFs) has been reported as well.

The results of the daily ammonia emission rates ER_d and related uncertainties during the cycle for the case of study are represented in **Figure 2.5**. Coverage intervals are shown in this figure, defining an interval estimated to have a coverage level of 95 percent, calculated with the Monte Carlo analysis.

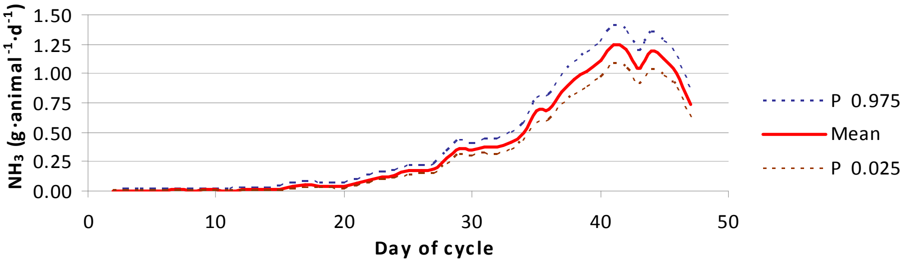


Figure 2.5. *Daily ammonia emission rates their symmetric 95% coverage intervals (values between the percentiles 0.025 and 0.975)*

The ammonia emission factor for a complete cycle and the annual emission factor are summarised in **Table 2.4**. In this table, both combined standard uncertainties and expanded uncertainties are shown for the variables ER_C and ER_Y.

The whole procedure followed here is consistent with the approach recommended for the uncertainty analysis in greenhouse gas emission inventories (IPCC, 2001), as well with a previous experimental work on gas emissions (Boriack *et al.*, 2004). Furthermore, it is consistent with the Bayesian point of view, because the use of prior information is possible according to Kaeker and Jones (2003).

Table 2.4. *Cycle and annual emission rates. Their related uncertainties are expressed as standard uncertainties in absolute and relative terms (u and %u respectively) and as 95% credibility intervals (95% C.I.)*

Parameter	Estimation	u (%u)	95% C.I.
ER_C (g·animal^{-1})	17.0	1.3 (7.5%)	14.6 – 19.6
ER_Y (g·place^{-1}·year^{-1})	97.2	7.7 (7.9%)	82.5 – 112.8

The contribution of the two main variables (ventilation flows and concentrations) to the combined uncertainty in daily emission rates is shown in **Figure 2.6**. Generally speaking, the lower the measured gas concentration is, the higher the corresponding relative uncertainty and thus, the higher the combined uncertainty of ER_d in relative terms.

At the beginning of the cycle, the gas concentrations are low and have high relative uncertainty because the measurement is near the instrumentation detection limit. Therefore, at the beginning of the cycle the measured concentration is the main contributor to the global uncertainty of ER_d. However, at the final stage of the growing period, concentrations are higher, and therefore, the relative uncertainties are lower. At this stage the contribution to global uncertainty of ventilation rate is higher than that of concentration.

It can be seen in **Figure 2.6** that the emissions are mainly produced at the end of the growing period, and it is reasonable to assume that the ventilation flow is the most influential contributor to the uncertainty in the final estimate.

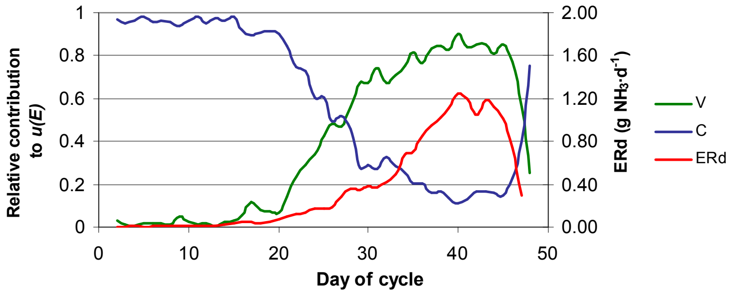


Figure 2.6. *Relative uncertainties in calculated ventilation flows (V), gas concentrations (C) and daily emission rates (ERd)*

When the total emission in a cycle is considered, which is defined as the sum of all daily emission rates during the growing period, the result is that 98% of the global uncertainty is caused by uncertainty in measuring the ventilation rate, whereas only 2% is caused by the uncertainty in measuring gas concentrations. There are two main reasons for this difference. The first reason can be deduced from **Figure 2.6**: the emissions are produced mainly at the end of the growing period, and therefore, it is reasonable that the ventilation rate is the principal contributor to the global uncertainty when the sum is calculated.

The second reason for this difference is that the measurement system for concentrations is considered to give independent results during the cycle, whereas the ventilation flow is not independent, since the same calibration curve is used during the whole experiment. Statistically, there about 600 repetitions of a measurement of gas concentration, whereas only one repetition of the calibration curve was obtained, and therefore the error associated with the concentration expressed as the sum of all measured emissions throughout the cycle is much lower than the error associated with the calibration of the fans.

2.4. Conclusions

Uncertainty analysis has been proposed as a tool to estimate the quality of calculated emission rates from animal buildings. This analysis consists of three main steps: formulation, propagation and summarizing.

In this study, the calculation of hourly and annual emission rates was used as an example to demonstrate the application of uncertainty analysis. The use of diagrams to identify the influencial variables was considerably enlightening because it provided a clear understanding of the calculation process as well as the identification of the uncertainty sources.

Although a special effort has been made to quantify the uncertainty sources, the PDFs for the model input variables must be subjected to further revision, since the experience when long-term measurements are available can lead to better estimates of these uncertainty sources.

The use of numerical methods to calculate the combined uncertainty was also proposed in this work for experimental research on gas emissions. In the uncertainty analysis of national gas emissions inventories, these methods have been widely used and accepted, because they are equivalent in many aspects to the analytical treatment of uncertainty. They also have the main advantage of dealing with diverse PDFs. In this context, the procedure followed here is consistent with the Bayesian view.

Results can be reported in a very comprehensive way when the uncertainty analyses are performed, and inference can easily take place. For the example used in this chapter (emission of ammonia in a broiler farm under summer conditions), an annual emission rate of 97.2 g of ammonia per place and year was reported. This information is complete in that the uncertainty expressed as a coefficient of variation was 7.9% of the reported value, and the 95% coverage interval was 82.5 – 112.8 grams of ammonia per place and year.

The contribution of each input variable to the global uncertainty was evaluated and gas concentrations were identified as the main uncertainty source in individual measurements, particularly when low gas concentrations are measured. However, ventilation flow was identified as the most important contributor to the final uncertainty (98%). This analysis is crucial to improve the quality of the measured data: special effort should be made to reduce uncertainty in the determination of ventilation flows. This variable is further studied and analysed in chapter 3.

Acknowledgements

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Chapter 3

Direct measurement of ventilation flows in a mechanically-ventilated commercial livestock farm

Direct measurement of ventilation flows in a mechanically-ventilated commercial livestock farm

Abstract

Emissions from animal housing are usually measured using air mass balances in the farm buildings, but this system leads to considerable uncertainties resulting from inaccurate measurements of air flows, especially in naturally-ventilated buildings. This study evaluates a system to measure ventilation flow in a mechanically-ventilated commercial farm with constant flow fans. The system consists of a properly protected, low voltage DC circuit connected to the signal contacts of the fan motor relays, considering safety criteria for both farm and workers. In this case, 16 fans were simultaneously monitored, but the system is easily adaptable to other farm dispositions with numerous fans. The system yields accurate data for the status of each fan and hourly ventilation flow, provided that the exhaust capacity of each fan is known. Uncertainties in the measurements were evaluated using numerical methods, being lower than 10% of the measured value in most cases. Cost-effectiveness of the system is also reported. The results are valuable to determine total emissions and temporary emission patterns, because daily variations in ventilation rates can be registered, and uncertainty results can be used as a source for the calculation of the emission rates.

Keywords: ventilation flow, uncertainty analysis, gas emissions, circuit, fans.

3.1. Introduction

Livestock production accounts for the majority of ammonia (NH_3) emissions to the atmosphere (Battye *et al.*, 1994; ECETOC, 1994). It is also a considerable source of greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O) (IPCC, 2000). Emissions from animal housing are a crucial part of total emissions from livestock production, together with manure management and land application of manure, and these emissions can be evaluated by means of mass balances, micrometeorological methods and tracer gas techniques (Phillips *et al.*, 2000).

Mass balance methods are frequently used, usually in the form of static or dynamic chambers of different sizes, depending on the emitting surface to be evaluated (Greatorex, 2000). In order to quantify emissions from animal housing facilities, the total volume of the housing building can be used as a volume control to measure gas emissions, as it has been explained in chapter 2 (Phillips *et al.*, 1998).

The two main parameters involved in gas emission measurements are gas concentrations and ventilation flows in the building, according to Equation 2.1 in chapter 2. Nowadays, gas concentrations can be accurately measured with the help of the technical advances in instrumentation such as photoacoustic or FTIR spectroscopy (Greatorex, 2000; Phillips *et al.*, 2001), and diverse measurement protocols have been established (*e.g.* Heber *et al.*, 2001). However, ventilation flux calculations may be much more complicated, particularly in naturally-ventilated buildings where only indirect methods (such as heat, water or CO_2 balances) can be used. In the case of mechanically-ventilated buildings, direct or indirect methods are possible (Blanes and Pedersen, 2005; Li *et al.*, 2005; Pedersen *et al.*, 1998), although direct methods are usually preferred, as they tend to be more accurate when correctly performed. According to Hoff *et al.* (2004), direct measurement methods for ventilation flow evaluation are classified into two groups: Fan Indication Methods (FIMs) and Fan Rotational Methods (FRMs). In the FIMs, total ventilation flow in the building is calculated considering activity (on-off status) and extraction capacity of each fan.

Fan operation may be measured by using vibration switches, mercury tilt switches and limit or "whisker" switches, but all have been reported to have limitations in long-term measurements (Muhlbauer *et al.*, 2006). Magnetic field switches are also commercialised for these purposes, but fans are usually electromagnetically isolated, and thus, they cannot be used in all farms. Induction operated current switches (ICS) have been also reported to be reliable and economical, but they must be installed at each fan (Muhlbauer *et al.*, 2006), resulting in an expensive and time-consuming process, especially when many fans must be monitored.

Another possibility for monitoring the on/off status of each fan consists in using the ventilation controller system already installed in the farm itself. The main advantage of this method is that all fans can be simultaneously monitored with a single device. However, it requires keeping the measurement system in a clean area of the farm, minimising the potential damage caused by dust, gases or animals. On the other hand, the cost of the measurement system is reduced, especially in farms where many fans are installed (*e.g.* poultry buildings). Regarding its disadvantages, Muhlbauer *et al.* (2006) identified the two main drawbacks of this system: the inability to detect possible motor failures and the difficulty in detecting fans operated manually. Motor failures are not frequent in commercial farms and can be detected by proper supervision. Regarding the second disadvantage, both manual and automatic operation of fans can be detected if the proper connections of the system are selected.

The ventilation flow of each fan must be carefully evaluated, since it is affected by the pressure drop (ΔP) inside the building (Gates *et al.*, 2004). Theoretical performance curves relating pressure drop and ventilation flow are usually provided by the manufacturer. However, they should not be directly applied, since the ageing and dirtiness of the mechanisms, as well as the shutters themselves, reduce the extraction capacity of fans (Simmons and Lott, 1997).

Uncertainty estimates in ventilation rate are essential to determine the quality of calculated emission rates, and these estimates can be evaluated according to the general rules of combined uncertainty explained in chapter 2 (Ellison *et al.*, 2000). These estimates are rarely reported for gas emissions in the literature, but they are an essential indicator of the quality of the measured data.

Ventilation flows are useful not only to calculate gas emissions, but also to evaluate the ventilation systems in relation to ventilation requirements for an adequate rearing of the animals and animal welfare.

There are two objectives of this work: (1) to design and implement a system for continuously determining the total ventilation flow in commercial mechanically-ventilated poultry houses (with 1 to 16 fans), based on the measurement of the ventilation flow of each individual fan and the continuous register of fans operation (on/off); and (2) to analyse the reliability of these measurements by means of uncertainty analysis using numerical methods (Monte Carlo). This study is focused as a necessary previous step to estimate gas emission rates from poultry buildings and their associated uncertainties.

3.2. Materials and Methods

The developed ventilation flow measurement system was originally devised to measure the ventilation flow in a specific mechanically-ventilated broiler house. However, the system is easily adaptable to different building layouts. In this chapter, a general description of the electrical circuit to monitor the fans activity will first be provided. The chapter will then focus on the application of the monitoring system to a specific poultry building.

3.2.1. Site description

The building described in this chapter, in which the monitoring system was tested, was a 110 x 13 m transversal mechanically-ventilated commercial broiler house located in Villareal (Castellón, Spain). The building was 11 years old. It has 16 triphase exhaust fans controlled by a central computer. Two types of fans were installed: nine large fans (LA-systems ES-140, 1.28 m diameter, 0.74 kW power and nominal ventilation flow 34,956 $m^3 \cdot h^{-1}$ at $\Delta P = 0$ Pa); and seven small ones (Ziel Abegg FC063-6D_4I.3, 0.68 m diameter, 0.58 kW Power and nominal ventilation flow 12.750 $m^3 \cdot h^{-1}$ at $\Delta P = 0$ Pa).

Continuous measurements were taken during summer (20th July 2006 to 3rd September 2006) and winter (27th December 2006 to 31st January 2007), which corresponded to a complete rearing period in summer and an almost complete one in winter, since the cycle started on 15th December. The duration of the rearing period was 48 days. After installing the system, ventilation flow was measured under the normal rearing conditions of the commercial farm (*i.e.* average number of animals 21,000 and rice hulls as bedding material). During the measurement period, pressure drop was daily determined using a pressure drop meter (Testo ® 512; range 0 – 200 Pa; precision 2 Pa) and outside climate conditions (air temperature and moisture, atmospheric pressure and solar radiation) were monitored and recorded every ten minutes by a weather station (HOBO, Onset Computer Corp., Pocasset, Mass.).

3.2.2. Operation status of the fans

All fans were electromagnetically isolated, and therefore the use of magnetic switches was not possible. Thus, a system was devised for determining the operation status (on/off) of the fans, consisting of a low voltage DC electrical circuit connected to the existing 230 V AC circuit used by the environmental control system in the farm. The circuit was designed using relays and resistors connected in such a way that a change in the operation status of a fan involved a change in the status of the corresponding relay, and thus a change in the voltage (according to Ohm's Law) that can be detected by a voltage data logger.

The circuit was designed according to safety and effectiveness criteria, and its cost was also evaluated. Operation statuses of the fans were recorded every 90 seconds by a voltage data logger (HOBO H08-004-02, precision 0.010 V, Onset Computer Corp., Pocasset, Mass.).

3.2.3. Ventilation flow

Ventilation flows exhausted by each kind of fan (Q) were determined at different levels of pressure drop (ΔP) in order to obtain individual performance curves under the conditions of the experiment. Ventilation flows were calculated (Equation 3.1) from the average air velocity at the exhaust section ($\bar{V}$) and the surface exhaust area (s). Average air velocity was calculated from air velocity measured at 24 different locations in a cross section 20 cm before the fans, using a hot wire anemometer (Testo® 425; measurement range 0 to

20 m·s^{-1}; precision 5% of reading), and following a recommended procedure (ASHRAE, 2001).

$$Q = \bar{v} \times s \qquad \text{(Equation 3.1)}$$

Ventilation flows were calculated at different *ΔP* (*i.e.* 0, 15, 30 and 45 Pa), all within the usual range of *ΔP* at this building. Pressure drop was set at the target values by using the environmental control system, which modified the inlet openings. *ΔP* values were then confirmed by measurements taken by a differential pressure meter (Testo ® 512; range 0 – 200 Pa; precision 5 Pa). Performance curves were obtained from measured data by lineal regression analysis, using the *Proc Reg* of SAS (SAS, 2001) and according to the model shown in Equation 3.2:

$$Q_{Pi} = \alpha + \beta \times \Delta P_i + \varepsilon_i \qquad \text{(Equation 3.2)}$$

Where Q_{Pi} is the predicted ventilation flow of the fan (m^3·h^{-1}); ΔP_i is the pressure drop (Pa); α and β are the model parameters, and ε_i is the model error. Measurements were made on one large fan and one small fan, assuming that all fans of the same size had the same performance, and finally, two ventilation performance curves were obtained, one for each type of fan.

The total ventilation flow in the building at each moment was estimated from the ventilation flow of each fan (predicted from the measured *ΔP* and the performance curves), and the activity of each fan, determined by the developed monitoring system (Equation 3.3):

$$V = \sum_{i=1}^{n} a_i \times Q_{Pi} \qquad \text{(Equation 3.3)}$$

Where:

V: total ventilation flow at the entire animal house (m^3·h^{-1})

a_i: activity of each fan *i*, defined as the time that the fan is in operation (on) in relation to the total time

Q_{Pi}: predicted ventilation flow at each fan *i* (m^3·h^{-1})

3.2.4. Uncertainty analysis

In order to determine the uncertainty of the ventilation flow estimated by this method, an uncertainty analysis of the measurements was performed, following the three main steps: formulation, propagation and summarizing (JCGM, 2006). The reason for this analysis is that the determination of the ventilation flow is a principal source of uncertainty when measuring gas emissions from an animal building (Gates *et al.*, 2004).

a) <u>Formulation stage</u>

The measurand is the total ventilation flow ($m^3 \cdot h^{-1}$), which depends on the activity of each fan and the predicted ventilation flow at each fan, according to Equation 3.3. The measurement process is outlined in **Figure 3.1**: the ventilation flow at each fan was calculated from the measured pressure drop, using the performance curve obtained for each type of fan (Equation 3.2). Performance curves were obtained from pressure drops measurements and ventilation flow estimations. Ventilation flows were estimated from air velocity averaged from measurements taken at different locations and the measured area of the cross section.

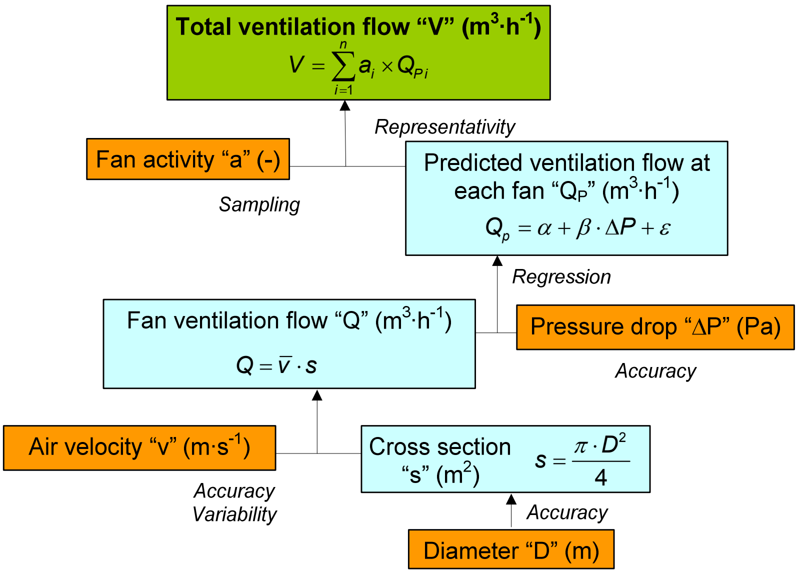

Figure 3.1. *Outline of the total ventilation flow estimation process and identification of uncertainty sources*

The sources of uncertainty identified in the ventilation flow estimation process are related with the sampling error, the inaccuracy of the different direct measurements taken, the intrinsic variability of air velocity measured at the outlet sections, the error of the regression analysis, and the selection of specific fans for fan performance tests.

The quantification of the uncertainty sources identified in **Figure 3.1** is shown in **Table 3.1**. PDFs are assigned to each parameter according to data provided by the manufacturers and assumed distributions.

Fan activity (a) was estimated by transforming the measured voltage into fan operation status (on/off) every 90 seconds (*i.e.* 40 operation status data per hour and fan), and therefore the estimated percentage of time that a fan is in operation had an associated sampling error which is described by a binomial PDF (Jurek *et al.*, 2007). Equation 3.4 in **Table 3.1** describes the sampling error in infinite populations according to the standard deviation of a binomial distribution, where p and q represent the proportion of time that each fan is active or inactive, respectively; and n is the sample size (40). When the sampled population is finite, Equation 3.4 overestimates the real uncertainty. Binomial distributions can be very asymmetric, and numerical methods are thus necessary to model the uncertainty propagation of this distribution.

Uncertainty sources arising from predicted ventilation flows of each fan (Q_P) were related to the regression error of Equation 3.2, in addition to the fact that the fans selected for determining the performance curves may not fully represent the remaining fans. The regression error was calculated by the standard errors of the coefficients $u(\alpha)$ and $u(\beta)$, which were obtained from the regression analysis carried out by SAS. The correlation between the least-squares coefficients $r(\alpha,\beta)$ was estimated with Equation 3.5 in **Table 3.1**, according to ISO (1995). The uncertainty associated with the selection of specific fans for carrying out the performance tests $u(r)$ was quantified as 3% (Simmons and Lott, 1997), and a normal distribution was proposed.

Uncertainties of pressure drops (ΔP), cross section areas and air velocities were associated with the accuracy of the corresponding direct measurements $u(a)$ and were calculated based on the specifications of the measurement devices, assuming a rectangular (or uniform) PDF according to the recommendations of JCGM (2006). The intrinsic variability of the air velocity measured at n = 24 locations of the outlet sections was an additional uncertainty source of the average air velocity estimations *u(v)*, and was quantified according to a shifted and scaled t-distribution with ν = *n-1* degrees of freedom, since it is obtained from a finite number of direct measurements (JCGM, 2006).

Table 3.1. *Evaluation of the uncertainty components and probability density functions assumed*

Parameter	*Uncertainty* source	*Quantification*	*PDF*
Fan activity	Sampling	$u(s)=\sqrt{\frac{p\cdot q}{n}}$ (Eq. 3.4)	$\frac{B(n,p)}{n}$
Air velocity	Precision	*u(a)* = 5% of value (manufacturer)	*R (0.95, 1.05)*
	Variability	*u(v)* = standard deviation of mean of measured values	$\bar{x}\pm t_{\nu}\cdot\frac{s_i}{\sqrt{n}}$
Fan diameter	Precision	*u(a)* = 0.005 m	$R(\bar{x}-0.005,\bar{x}+0.005)$
Pressure drop	Precision	*u(a)* = 5 Pa (manufacturer)	*R(ΔP - 5 , ΔP + 5)*
Calibration curve	Regression error	*u(α)* = standard error of intercept *u(β)* = standard error of slope $r(\alpha,\beta)=-\frac{\sum x_i}{\sqrt{n\sum x_i^2}}$ (Eq. 3.5)	*N [α, u(α)]* *N [β, u(β)]*
	Represent-ativity	*u(r)* = 3% (Simmons and Lott, 1997)	*N (1, 0.03)*

B(n,p) Binomial distribution with *n* repetitions and probability *p*

R(x_1,x_2) Rectangular or uniform distribution with lower limit x_1 and upper limit x_2

t_ν Student-t distribution with ν = *n-1* degrees of freedom, where *n* is the number of measurements

N(μ,σ) Normal distribution with mean μ and standard deviation σ

The PDFs corresponding to the uncertainty associated to representation, accuracy and variability errors in **Table 3.1** were considered as scaled multiplicative functions with means equal to 1 with the corresponding relative uncertainty. Therefore, the corresponding uncertainty was introduced in the model without altering the final value (Ellison *et al.*, 2000:63).

Correlations between the variables were studied using the procedure *Proc Corr* of SAS System® (SAS, 2001).

b) Propagation stage

The combined uncertainty (*i.e.* the uncertainty of the total ventilation flow) cannot be calculated applying the law of the propagation of the uncertainty as indicated by Ellison *et al.* (2000), because non-normal PDFs are considered. Monte Carlo Methods (MCM) were therefore carried out, by means of the software RiskAMP Monte Carlo Add-In Library version 2.70 for Excel (Structured Data, 2005). For each simulation the software takes a random number of the given PDFs (normal, uniform, student-t or binomial, according to **Table 3.1**) and then a simulated result of V is obtained according to the calculation schema provided in **Figure 3.1**. The number of simulations selected was $M = 10^5$. The software remembers the result for each trial, reporting as a final result the target information such as mean value, standard deviation, percentiles, etc.

c) Summarizing stage

Mean, combined uncertainties and the 95% coverage intervals were obtained from the resulting probability distribution of the ventilation flow. These values were directly obtained from the simulated PDF obtained by the RiskAMP software.

The contribution of each source to the global uncertainty was calculated numerically as explained in chapter 2.

3.3. Results and discussion

3.3.1. Electrical circuit description

The developed system for monitoring fans activity consisted on connecting a 2.2 V DC electrical circuit to the existing 230 V AC circuit used by the environmental system controllers (**Figure 3.2** and **Figure 3.3**). Each monitoring circuit was designed to detect 16 voltage levels, and therefore it was able to simultaneously monitor the operation status of four fans, as 2^4 voltage levels are possible from four fans working with two possible operation statuses (on/off). The monitoring circuit consisted of four 230 V AC relays (L1, L2, L3 and L4) and four resistors (R1, R2, R3 and R4) connected in parallel in such a way that the output voltage varied depending on the status of the different fans. According to **Figure 3.2**, a change in the operation status of a fan involves a change in the status of the corresponding relay, and thus a change in the voltage detected by the data logger. Voltage data was then used to determine the operating status of each fan, according to **Table 3.2**. Four identical circuits were used to evaluate the operation status of the 16 fans in the farm.

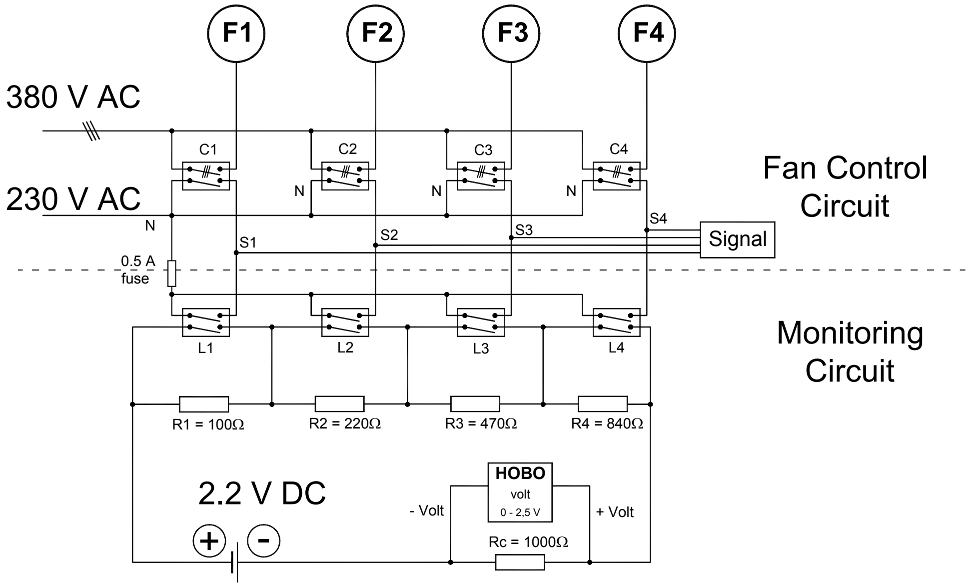

Figure 3.2*. Schematic representation of the electrical circuit designed for simultaneously monitoring four triphase fans (F1 to F4), controlled four relays (C1 to C4). The signal is converted into a 0 – 2.2 V DC signal using four relays (L1 to L4) connected in parallel with four different resistors (R1 to R4), and is registered by a voltage data logger. The circuit is protected with a 0.5 A fuse*

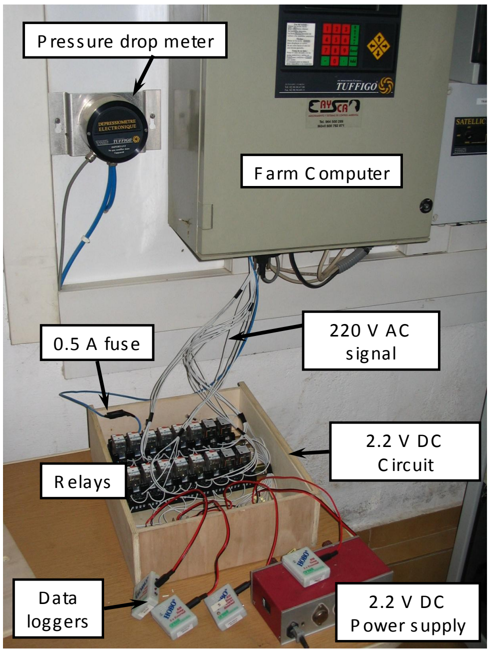

Figure 3.3. *View of the system for monitoring fan activity, the power supply, data loggers and relays, during a typical test*

Table 3.2. *Output voltage depending on the operation status (on/off) of each fan (missing values indicate off status)*

Operation status				Output
Fan 1	Fan 2	Fan 3	Fan 4	voltage (V)
				0.84
On				0.88
	On			0.92
		On		1.03
			On	1.23
On	On			0.96
On		On		1.08
On			On	1.30
	On	On		1.15
	On		On	1.40
		On	On	1.67
On	On	On		1.21
On	On		On	1.50
On		On	On	1.80
	On	On	On	2.00
On	On	On	On	2.20

The investment cost is detailed in **Table 3.3**. It can be seen that relays and data-loggers were the most expensive components. The circuit permits the simultaneous measurement of 16 fans, being easily adaptable when fewer fans are to be controlled. The cost per fan controlled (including data logger) is 41.13€, compared to the cost of other as devices provided by Muhlbauer *et al.* (2006): 25.16€ for an ICS device; 2.54€ for a vibration switch; 3.82€ for a mercury tilt switch and 12.74€ for a whisker switch, not including in any case the cost of the logging device[1].

Table 3.3. *Investment cost for the designed circuit and data logger*

Component	No. units	Unitary cost	Total cost
Relay (Zelio RXN 21E12BN)	16	15.00€	240.00€
Data Logger (HOBO H08-004-02)	4	95.00€	380.00€
Wire (0.21 mm^2)	15	0.50€	7.50€
AC-DC transformer	1	30.00€	30.00€
0.5 A Fuse	1	0.70€	0.70€
		Total cost	**658.20€**

The monitoring system was installed in the described poultry building, and it was used for monitoring the fans activity (and therefore the total ventilation flow) throughout two rearing periods. The system did not failed to measure at any time during the two measurement periods (48 days per period). Furthermore, the data analysis to calculate hourly ventilation rates was found to be much easier and less time-consuming than that related to magnetic or vibration switches. There are two reasons for this: first, direct hourly fan activity could be obtained with simple operations; second, many fans are controlled at the same time. As a consequence, data corresponding to the circuit controlling 16 fans during 8 days needed a 1-hour data processing time, whereas a magnetic switch required 2 hours for each fan and 4 days of measurement.

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[1] Original costs were reported in US dollars. Conversion to euros were made using the conversion value as of 1st April 2008 (1 € = 1.56 US $)

3.3.2. Fan performance tests

A preliminary test was carried out to determine the performance curves of the installed fans, as well the uncertainty associated with the individual ventilation flow estimated from air velocity and area measurements. The measured values and uncertainties in ventilation flow estimations are shown in **Table 3.4**.

Table 3.4. *Air velocity and fan performance calculations: average values and uncertainties*

Fan	*ΔP (Pa)*	*Air velocity ($m \cdot s^{-1}$)*			*Flux flow ($m^3 \cdot s^{-1}$)*		
		Value	*u(v)*	*u(a)*	***Value***	*u(Q)*	*%u(Q)*
Large	0	**4.89**	*0.15*	*0.06*	**22,664**	*755*	*3.33*
	15	**4.32**	*0.26*	*0.06*	**20,018**	*1,223*	*6.11*
	30	**4.19**	*0.20*	*0.05*	**19,425**	*985*	*5.07*
	45	**3.74**	*0.18*	*0.05*	**17,302**	*880*	*5.09*
Small	0	**6.97**	*0.16*	*0.09*	**8,617**	*259*	*3.01*
	15	**6.26**	*0.36*	*0.08*	**7,742**	*447*	*6.16*
	30	**5.86**	*0.35*	*0.08*	**7,250**	*458*	*6.32*
	45	**5.40**	*0.31*	*0.07*	**6,682**	*403*	*6.02*

The variability in the measured air velocity *u(v)* was identified as the main source of uncertainty in the estimation of the ventilation flow corresponding to a specific pressure drop. Improved measurement methods could significantly reduce this uncertainty source (Gates *et al.*, 2004).

Performance curves obtained from the regression analyses are shown in **Figure 3.4**. Estimated ventilation flows were on average 34% lower than those reported by the manufacturer. This differences higher than those reported by Simmons and Lott (1997), who found a 10.9% reduction with shutters alone, and as much as 24% in old, dirty fans. A reduction in the actual ventilation flow can imply a decrease in the ventilation efficiency, which results in an increase in energy consumption.

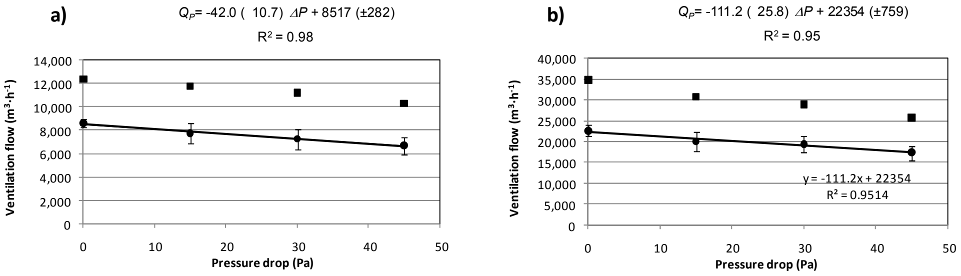

Figure 3.4. *Calibration curves used to determine ventilation flow. a) Small fans; b) Large fans. Square marks indicate manufacturer data, whereas round marks refer to on-farm measured data. Error bars indicate two times the standard deviation of mean (SDOM) and represent uncertainties in measurement corresponding to a credibility interval of 95%. Values in parenthesis in the regression equations indicate standard errors*

3.3.3. Estimated total ventilation flow

As a result, hourly ventilation flows were obtained, which increased with the birds' age, and was highly dependant on the outdoor temperature (**Figure 3.5**). Therefore, daily variations of the total ventilation flow occurred, showing lower values during the night. Daily variation of ventilation flow is essential information in order to study emission rates in detail. The comparison between the two measurement periods also showed that estimated ventilation flow during summer was higher than that estimated in winter.

Ventilation flow estimated during winter period appeared to be highly dependent on the measured outdoor temperature. Average ventilation flow was 4.1 $m^3 \cdot h^{-1} \cdot animal^{-1}$ for the measurement period in summer whereas for the winter period it was 1.8 $m^3 \cdot h^{-1} \cdot animal^{-1}$. This fulfils the general recommendation in the ASAE Standards (2003): 1.8 $m^3 \cdot h^{-1} \cdot kg^{-1}$ in summer, and a minimum ventilation of 0.18 $m^3 \cdot h^{-1} \cdot animal^{-1}$ in winter. However, according to this standard, the necessary ventilation rates should preferably be calculated using sensible and latent heat balances.

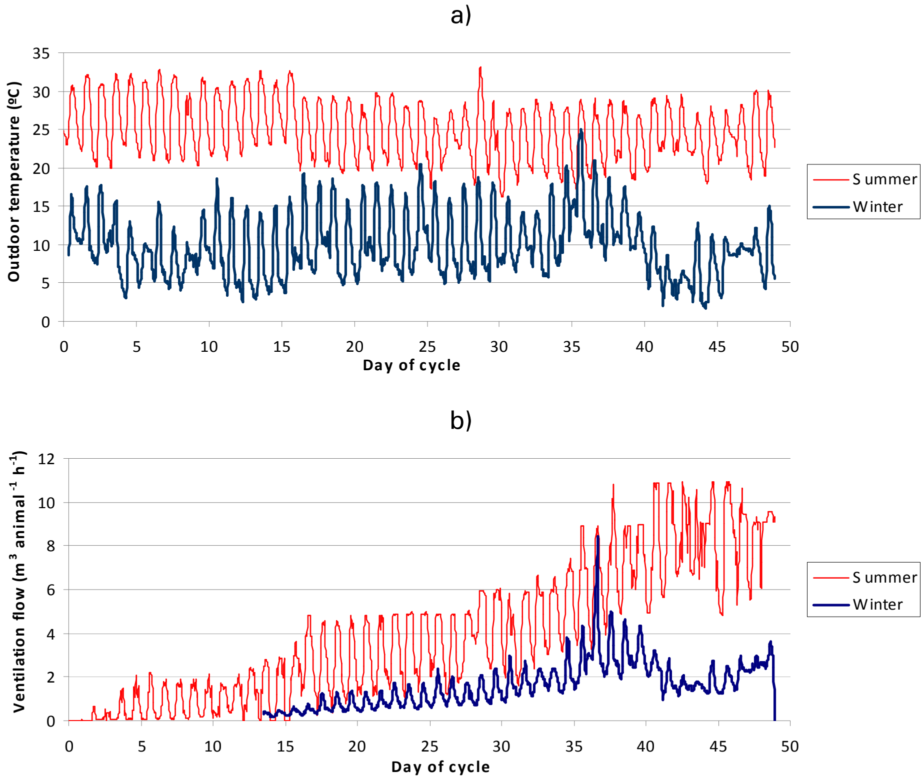

Figure 3.5. *Outside air temperature (a) and ventilation rate (b) during the rearing period in summer and winter*

3.3.4. Uncertainty analysis

Uncertainty analyses were carried out from measurements taken during the two measurement periods, showing that, during the whole measurement period, the uncertainty associated with the estimated daily ventilation flow was less than 10% of the estimated value (**Table 3.5**).

Table 3.5. *Average values of daily ventilation flow (V) expressed in cubic meters per animal and hour, and their associated uncertainties expressed in terms of percentages of the measured value, %u(V)*

Day	Summer		Winter		Day	Summer		Winter	
	V	%u(V)	V	%u(V)		V	%u(V)	V	%u(V)
1	0.06	15.3	n.d.	n.d.	25	3.57	7.10	1.33	7.34
2	0.14	11.9	n.d.	n.d.	26	3.10	6.81	1.25	7.31
3	0.40	8.47	n.d.	n.d.	27	3.64	6.99	1.41	7.25
4	0.63	8.16	n.d.	n.d.	28	4.80	7.05	1.59	7.18
5	0.81	8.06	n.d.	n.d.	29	4.49	6.94	1.78	6.71
6	0.80	7.88	n.d.	n.d.	30	4.01	6.93	1.89	6.99
7	0.85	7.67	n.d.	n.d.	31	4.18	6.85	1.98	7.05
8	0.90	7.60	n.d.	n.d.	32	4.72	6.91	2.11	7.01
9	0.79	7.27	n.d.	n.d.	33	4.92	6.88	2.34	5.88
10	0.95	7.09	n.d.	n.d.	34	5.42	6.83	2.83	5.01
11	1.11	7.06	n.d.	n.d.	35	6.28	6.77	4.44	4.76
12	1.46	7.02	0.36	9.04	36	6.28	6.74	3.46	4.70
13	1.71	7.29	0.33	8.40	37	6.80	6.70	3.30	4.77
14	1.98	7.33	0.42	8.18	38	7.48	6.42	3.47	4.73
15	2.29	7.25	0.51	7.97	39	7.67	6.62	2.81	5.86
16	3.09	7.18	0.70	7.86	40	7.14	6.58	1.99	6.53
17	2.50	6.99	0.79	7.77	41	8.47	6.00	1.71	6.73
18	2.57	7.08	0.85	7.72	42	8.71	6.03	1.73	6.70
19	2.56	7.11	0.85	7.66	43	7.90	6.14	1.90	6.49
20	2.82	7.16	0.90	7.60	44	8.89	6.11	1.96	6.58
21	3.02	6.88	1.07	7.54	45	7.80	6.02	2.28	6.33
22	3.37	7.09	1.07	7.50	46	8.85	5.68	2.72	6.05
23	3.44	6.99	1.02	7.48	47	9.60	5.82	2.77	5.28
24	3.60	7.09	1.39	7.34					

n.d. no measurements were taken on these days

Figure 3.6 shows hourly ventilation flows and uncertainties, during one specific day (day 20 of the rearing period) both in summer and in winter conditions.

The hourly ventilation flow shows an uncertainty function which is positively asymmetric. The asymmetry is partly due to the asymmetry in the binomial function involved in the calculation, and partly due to the multiplication of the probability functions.

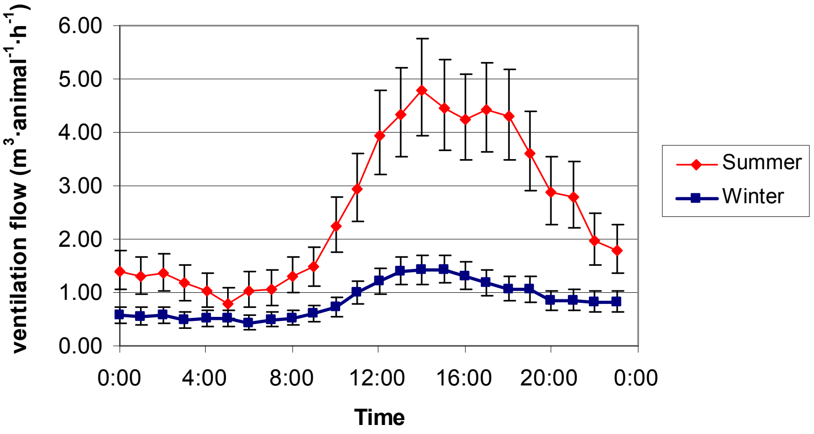

Figure 3.6. *Daily variation in ventilation flow on the 20th day of the rearing period in summer (07th August 2006) and in winter (03rd January 2007). Error bars show the symmetric 95% credibility interval*

Ventilation flow can be estimated at animal houses for different purposes, such as; environmental control and fans performance assessments, and animal welfare investigations. However, the evaluation of gaseous emissions from animal houses has become one of its most important applications.

The contribution of the ventilation flow estimated at each fan (Q_P) and the activity measured by the monitoring system (a) to the final uncertainty (uncertainty of the total ventilation flow estimation) is represented in **Figure 7** for the two experiments. The contributions of large and small fans are shown separately in order to better evaluate the uncertainty sources. This figure shows that the estimation of the activity of the fans is the major source of uncertainty at low ventilation flows (approximately lower than 20,000 m^3·h^{-1}), whereas at high ventilation flows, the estimation of the ventilation flow exhausted by each fan becomes crucial.

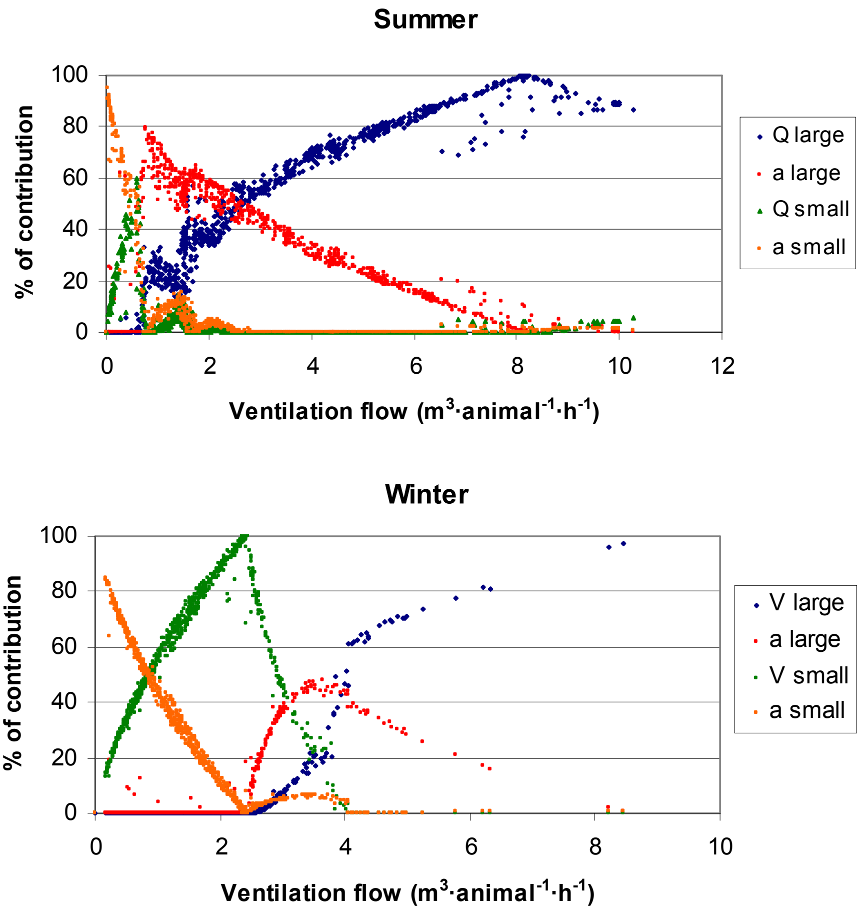

Figure 3.7. *Relative contribution of the input variables in the global uncertainty of flux flow in the poultry farm in summer and winter. Input variables are ventilation flow extracted by each fan (Q) and fan activity (a) in large and small fans, separately.*

The results of this study indicate that when the total ventilation flow was low (approximately less than 1 $m^3 \cdot h^{-1}$ animal^{-1}), the uncertainty associated with the determination of the fan status, was the main source of uncertainty for the final ventilation flow, in comparison to the contribution of the uncertainty due to the individual ventilation flow estimations. Therefore, other methods for total ventilation flow estimations such as vibration or magnetic switches and

ICS might provide better results than that proposed here. However, when the ventilation flow was higher, the uncertainty originated by the monitoring system contributed by less than 10% to the total uncertainty of the ventilation flow. As gaseous emissions are usually higher at the end of the cycle, and in this period, high ventilation flows are frequently needed, the monitoring system uncertainty as defined in this study will not significantly contribute to the uncertainty in gas emission estimates.

3.4. Conclusions

A simple method has been developed to simultaneously control the operation status of 16 fans in a commercial broiler farm. The circuit consists of a 2.2 V DC circuit connected to the fan operation box of the building. This circuit meets the following requirements: safety for the user, safety for the farm installations, easy to mount, durable, feasible, accurate, versatile, affordable and data output are easy to process.

The system worked correctly throughout the two rearing periods, and hourly ventilation rates were obtained. This kind of information is very useful for emission rates estimates, since daily variations can be studied in detail.

The uncertainty analysis was a key point in this research, since the results must be accompanied by an estimation of their quality. Special effort was made to properly identify and quantify uncertainty sources, using procedures which are as objective as possible. The use of numerical methods has been successful: complicated relationships can be analyzed, and non-normal distributions can be used. Further effort has to be done, however, in precisely quantifying the uncertainty sources.

Uncertainties in average daily ventilation flow were lower than 10% of the calculated value. Fan activity sampling errors were in most cases lower than those corresponding to the extraction capacity of the fans. The identification of the impact of the uncertainty sources is the most effective way to improve the quality in ventilation rate measurements. Variability in measured air extraction capacity of each fan was identified to be the main uncertainty source, and thus efforts are needed to determine fan curves to reduce uncertainty in the results.

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Chapter 4

Gas emissions in two Mediterranean rabbit farms

Gas emissions in two Mediterranean rabbit farms

Abstract

Unlike other animal species, there is very little information about gas emissions from rabbit production. In this study, gas emissions (ammonia, carbon dioxide, methane and nitrous oxide) were measured in two rabbit farms by means of a mass balance in the air, taking into account ventilation flows and gas concentrations. Ventilation flow was calculated multiplying the measured airflow by the time of operation of each fan in the farm, while gas concentrations were measured using a photoacoustic gas monitor and an uncertainty analysis was carried out. A nitrogen balance was also performed to determine the partition of this element in the production of fattening rabbits. The experiments were conducted in Mediterranean summer and winter conditions, so as to evaluate the seasonal effect. As a result, gas emissions in fattening rabbits expressed per animal place and year varied between 61.7 and 138.4 g of ammonia, and between 20.8 and 37.8 kg of carbon dioxide; methane and nitrous oxide emissions were in most cases undetectable. For reproductive does, emissions per place and year varied between 500 and 575 g of ammonia, between 141 and 182 kg of carbon dioxide, and between 94 and 310 g of methane. Nitrous oxide emission was negligible. From the nitrogen balance in fattening rabbits, a value of 0.4 kg of N excreted per place and year was obtained, which is 59% of the total nitrogen intake. Ammonia emission from the building constituted 20% of the nitrogen loss from the total excreted nitrogen.

Keywords: rabbit production, gas emissions, ammonia, methane, nitrous oxide, carbon dioxide, nitrogen balance.

4.1. Introduction

According to FAO statistics the intensive rearing of rabbits for meat production is a specialised farming activity in certain countries with a total annual production of 1,162,000 in 2005 (FAOSTAT, 2007). Spain is the third major producer of rabbit meat after China and Italy, accounting for about 10% of the total world production, with a population of more than 16 million animals.

In Spanish commercial farms, rabbits are usually kept in cages in two separate phases. In the first phase, reproductive does are kept in individual cages where gestation and lactation occur, with a duration of 4 to 5 weeks from birth to weaning of the bunnies. The second phase is a fattening period in collective cages of 8 to 10 rabbits each, and it is 4 to 5 weeks long according to the demand of the market. In both phases the cages are about 60 cm above a pit for manure collection **(Figure 4.1)**. Manure is extracted every 2 or 3 months by means of a pull plug. The two phases occur in a repetitive cycle during the year, normally in separate buildings.

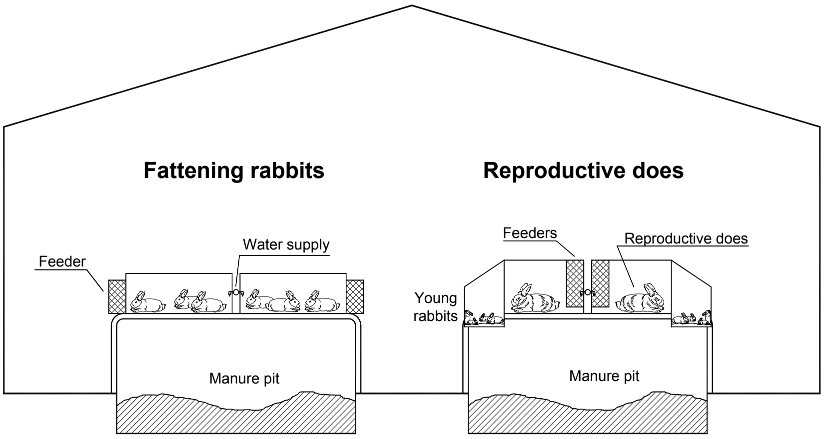


Figure 4.1. *Typical rearing system for fattening rabbits and reproductive does*

Rabbit breeding and feeding have been thoroughly studied, but the environmental implications are not so well known, and there are few scientific publications related to nitrogen balance and gas emissions in rabbit farms.

Emissions from rabbit production are currently not included in the Spanish gas emissions inventory (EEA, 2007), but this activity could be included if reliable data were available. Other countries such as Portugal and Italy include gas emissions from rabbit production, but using adapted data from other species, so scientific investigation is still pending.

Ammonia emissions arise from the relative inefficiency in the use of nitrogen by the animals: approximately two-thirds of the nitrogen intake is excreted as urine and faeces (European Commission, 2003), and a part of the excreted nitrogen is lost as ammonia, with three main consequences. First, ammonia is a pollutant contributing to acidification and eutrophication in the environment (Krupa, 2003). Second, the nitrogen loss reduces the fertilizer value of manure (Burton and Turner, 2003). And finally, ammonia has serious implications for human and animal health (Roney *et al.*, 2004). A first attempt to accurately determine the N cycle in the production of fattening rabbits was performed as a previous part of this study (Calvet *et al.*, 2006), where the results shown in **Figure 4.2** were obtained.

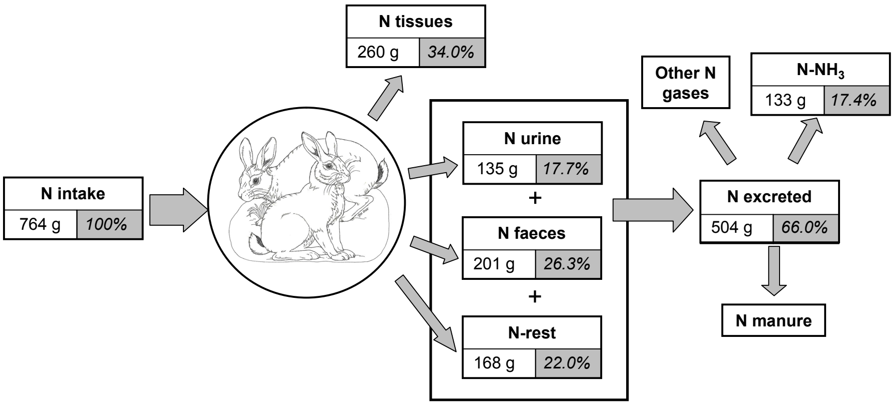


Figure 4.2. *N cycle for fattening rabbits (Calvet et al., 2006)*

As stated earlier, ammonia emission from rabbit production is normally not considered in gas emission inventories. **Table 4.1** summarises the proposed emission factors in the few countries that do consider these emissions; in contrast to this, **Table 4.2** shows all the values found in experimental studies.

It can be concluded that the amount of information is limited in comparison with that for other species such as poultry or pigs.

Table 4.1. *Ammonia emission factors used in national gas emission inventories*

Country	N excretion kg $N \cdot pl^{-1} y^{-1}$	Emission Factor kg $NH_3 \cdot pl^{-1} \cdot y^{-1}$	Comments	References
IPCC default	4.73 8.89	- -	(A) (B)	IPCC (2006)
Italy	0.6	0.16	(B)	APAT (2005)
Portugal	7.4	1.63	(A)	Gois *et al.* (2006)
The Netherlands	-	0.2 1.2	(B) (A)	Infomil (2002)
U.S.A.	-	2.8	(A)	Battye *et al.* (1994)

(A) Estimated for reproductive does; (B) Estimated for fattening rabbits

Table 4.2. *Experimental results on ammonia emissions in rabbit production*

Season of year	Manure management	Concentration ppm	Emissions kg $NH_3 \cdot pl^{-1} \cdot y^{-1}$	Source
		Reproductive does		
Summer	Manure belt	8.5 – 10.0	0.79 – 0.85	Hol *et al.* (2004)
Autumn	Manure belt	11.7 – 13.4	0.68 – 0.78	Hol *et al.* (2004)
		Fattening rabbits		
Winter	Slat	3.4 – 5.6	0.017	Michl and Hoy (1996)
Summer	Manure belt	4.3 – 5.2	0.13 – 0.17	Hol *et al.* (2004)
Autumn	Manure belt	4.2 – 4.7	0.08 – 0.11	Hol *et al.* (2004)
Winter	Deep pit	15 – 20	0.03	Calvet *et al.* (2006)
Summer	Deep pit	2 - 8	0.16	Calvet *et al.* (2006)

Greenhouse gas emissions from rabbit production are seldom reported in the literature. Methane production from enteric fermentation in rabbits differs from ruminants as a consequence of the different location of the bacterial activity. Enteric fermentation in rabbits takes place in the caecum, which is much more developed than in other species and accounts for more than 40% of the digestive tract. Two main consequences are derived from this fact (Gidenne, 1997). First, anaerobic bacteria have a poor environment in which to grow, and therefore enteric fermentation is less intensive in rabbits than in ruminants. Second, the animal can obtain no direct benefit from this fermentation, and so caecotrophy occurs, which is the excretion of two distinct types of faeces: soft faeces that can be consumed by rabbits again and hard faeces that are not consumed. Methanogenesis has been reported to be considerable in adult rabbits, but it is negligible in young suckling rabbits until 32 days of age (Piattoni *et al.*, 1996).

Methane is produced in the management of manure when anaerobic conditions occur, in two consecutive phases (Burton and Turner, 2003):

- Fast growth of acidogenic bacteria in a wide temperature range, producing organic acids and carbon dioxide.
- Growth of specific methanogenic bacteria, producing methane from organic acids.

Langer (2002) estimated that methane emission from rabbit manure was 42 nmol of CH_4 per hour and gram of faeces. Considering a total manure production of 27.5 kg faeces per place and year obtained in a previous work (Calvet *et al.*, 2006), an emission factor of 162 g CH_4 per place and year (for a reproductive doe) can be estimated. The reported methane emission factors in different national emission inventories are shown in **Table 4.3**.

Table 4.3. *Methane emission factors used in national gas emission inventories*

Country	Enteric	Manure	Comments	References
	(kg CH_4·pl^{-1}·y^{-1})			
IPCC def.	-	0.08		IPCC (2006)
Italy	0.08	-	(B)	APAT (2005)
Portugal	3.63 (1)	0.07-0.10	(A)	Gois *et al.* (2006)
Malta	0.1 (2)		(A)	Mallia *et al.* (2003)

(A) Estimated for reproductive does; (B) Estimated for fattening rabbits

(1) Calculated from horses, using a conversion for metabolic weight

(2) Calculated from goats (50 rabbits = 1 goat)

Nitrous oxide is produced in manure management under specific conditions (Monteny *et al.*, 2006) including a first aerobic phase (nitrification) and a second anaerobic phase (denitrification). In rabbit farms these conditions can occur in manure heaps after manure extraction; however, these conditions do not normally exist inside the barns (Blumetto and Torres, 2005).

Carbon dioxide from rabbit production is normally not considered as a greenhouse gas emission, since it is a part of the short-term closed agricultural cycle. This gas is produced by animal respiration and manure decomposition. Animal respiration accounts for 1.13 $L{\cdot}h^{-1}$ of CO_2 per kilogram of metabolic weight, which equals about 2 $g{\cdot}h^{-1}$ per kilogram of metabolic weight (CIGR, 2002), and this value is proposed as a way to indirectly measure ventilation rate in naturally-ventilated buildings (CIGR, 2002). Experimental results showed emission rates between 0.82 and 0.90 $L{\cdot}h^{-1}$ CO_2 per kilogram of metabolic weight (Kiwull-Schöne *et al.*, 2001; Kiwull-Schöne *et al.*, 2005). The amount of carbon dioxide emitted from manure depends on many factors (especially temperature and nitrogen availability), and represents about 20% of the total carbon loss in a building (Wolter *et al.*, 2004).

The two main objectives of this study were (1) to measure gas emissions (NH_3, CO_2, CH_4 and N_2O) in rabbit production in Spanish commercial farms, and (2) to quantify the components of the nitrogen cycle in the production of fattening rabbits.

4.2. Materials and Methods

4.2.1. Experiment layout

Gas emissions were measured in 2006 and 2007 in two rabbit farms in the province of Valencia. The first one (*Farm A*) corresponds to the experimental breeding farm in the UPV (Valencia, 39º29’01”N, 0º20’21”W, 15 m above sea level), and the studied building had 204 cages for fattening rabbits (about 1500 animals). The second farm (*Farm B*) is a commercial rabbit farm located 60 km north-west of Valencia (Alcublas, 39º38’32”N, 0º40’39”W, 800 m above sea level). In *Farm B* two buildings were studied: one for reproductive does (*Farm B1*) with 400 cages, and one for fattening rabbits (*Farm B2*) with

396 cages (approximately 3600 animals). Furthermore, in Farm A a nitrogen balance was performed for an entire fattening cycle (5 weeks). In this balance, N inputs (feedstuff consumption), N outputs (urine and faeces production) and N accumulation (animal tissues) were evaluated weekly. **Table 4.4** summarises the schedule of the measurements.

Table 4.4. *Schedule for gas emission measurements and nitrogen balance*

Farm	Task	Animal	Start	End
A	Gas emissions	Fattening rabbits	29-Jun-06	12-Jul-06
A	N balance	Fattening rabbits	26-May-06	27-Jun-07
$B1_{wint}$	Gas emissions	Reproductive does	19-Feb-07	03-Mar-07
$B2_{wint}$	Gas emissions	Fattening rabbits	19-Feb-07	03-Mar-07
$B1_{sum}$	Gas emissions	Reproductive does	15-May-07	03-Jul-07
$B2_{sum}$	Gas emissions	Fattening rabbits	15-Jun-07	03-Jul-07

Both farms follow the typical rearing system for rabbits shown in **Figure 4.1**, and are mechanically ventilated. Animals were fed *ad libitum*, on conventional rabbit feed.

4.2.2. Nitrogen cycle

In Farm A, a nitrogen balance at animal level was carried out in eight cages of nine animals each. The animals corresponded to the UPV line selected for longevity, according to the usual breeding programmes in Spain (Baselga, 2004). The balance was performed weekly during a complete fattening cycle, from weaning (day 28 of life and average animal weight 0.66 kg) to slaughter (day 61 and animal weight 1.84 kg). No distinction between males and females was considered.

Animal weight was monitored individually every week. Nitrogen content in the animal tissues was estimated in 29 g N/kg live weight for a fattening rabbit with a standard weight of 2.5 kg, according to the revision made by Maertens *et al.* (2005). For younger animal weights, a correction of 0.08 g N/kg live weight was used, because of the lower nitrogen content in younger animals.

Urine and faeces were collected separately using a 4 mm mesh for faeces, and a polyethylene layer collected the urine to a 8 L bottle under each cage (see **Figure 4.3**). The device was easy to assemble and dismantle, but was labour demanding since daily weighing of faeces and urine was required.

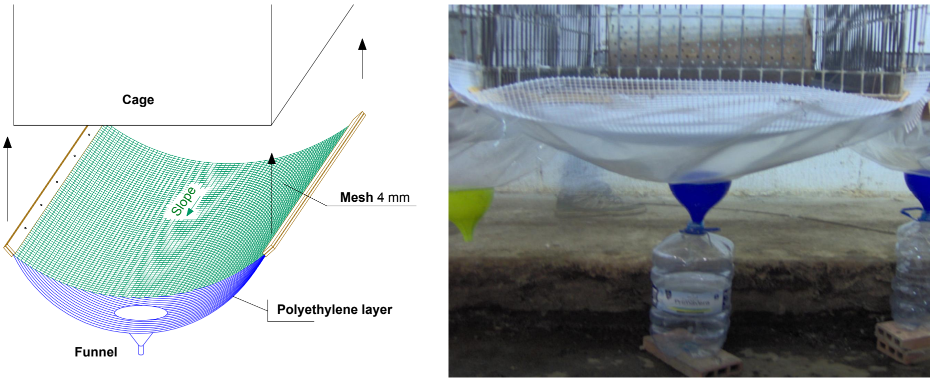


Figure 4.3. *Schema and final aspect of the urine and faeces collecting device*

Chemical analyses (dry matter, ash content and nitrogen) were carried out weekly. Dry matter was determined in repeated 1 g samples at 104°C until constant weight. For ash content, incineration (540°C, 4 hours) was carried out, and the Kheldahl method was used to determine the nitrogen content.

4.2.3. Emission estimates

Emissions were estimated by determining ventilation rates (*V*) and gas concentrations in the outlet and inlet gas (C_{outlet} and C_{inlet}).

$$E = \left(C_{outlet} - C_{inlet}\right) \cdot V \qquad \text{(Equation 4.1)}$$

Since the rabbit farms were mechanically ventilated, ventilation rates were calculated measuring the time of operation of each fan by means of a logging circuit and the calibration curve of the fans (see chapter 3). In this case, there were two exhaust fans in Farm A, one in Farm B1 and four in Farm B2, and therefore, the circuits were much simpler than the one described in chapter 3. The pressure drop, estimated on a weekly basis (Testo ® 512; measurement range 0 – 200 Pa; precision 2 Pa) was constant, between 10 and 15 Pa in all cases.

Gas concentration measurements were carried out using a photoacoustic multi-gas monitor for NH_3, CO_2, CH_4 and N_2O (Innova-1412) equipped with a gas multiplexing system which allowed consecutive measurements at eight points every two hours. Two internal measurement points were considered in Farm A and Farm B1, and four points in Farm B2. In all cases two external sampling points were used to determine background concentrations. The measuring system (**Figure 4.4**) was financed with FEDER funds.

Figure 4.4. *Gas measurement system including the photoacoustic gas monitor, a pneumatic multiplexing system and a computer for data logging*

4.2.4. Environmental conditions

The temperature and relative humidity were continuously measured both indoors and outdoors, using a data logger (HOBO H8-004-002) and a weather station (HOBO Weather Station), respectively. Temperature of the manure in the pit was recorded as well, using an air/water/soil temperature sensor (HOBO TMC6-HD).

4.2.5. Statistical analyses

An uncertainty analysis was performed according to the procedure explained in chapter 2 (see **Figure 2.3**) and following the three main stages of the uncertainty calculation: formulation, propagation and summarizing (JCGM, 2006). In the formulation stage, the uncertainty sources considered are detailed in **Table 4.5**.

Table 4.5. *Uncertainty sources and quantification in the determination of the annual emission rate in the two experiments*

Parameter	*Uncertainty source*	*Quantification*	*PDF*
C_{outlet} C_{inlet}	Instrument precision and sampling	ANOVA of measurements	$N\left(\bar{x}_i;\frac{RMS}{N_M}\right)$
	Cross interferences	Instrument calibration	Rectangular
No. animal places	Imprecision	Zero	Section 4.2.1
D_{cycle} D_{empty}	Variability	Revision of farm records over the previous five years	Section 4.2.1
Model	Physical validity	Zero (by definition)	-
Vent. rate	See chapter 3	See chapter 3	

In the propagation stage, the software RiskAMP Monte Carlo Add-In Library version 2.70 for Excel (Structured Data, 2005) was used to carry out the numerical simulation to propagate distributions. Finally, average values, standard uncertainties and 95% coverage intervals were reported.

Analyses of variance (ANOVA) were performed in order to determine whether significant differences between cages existed, in relation to the parameters involved in the determination of the nitrogen balance. Analyses were carried out using the *Proc GLM* procedure of SAS (SAS, 2001).

4.3. Results and discussion

4.3.1. Nitrogen cycle

The results for the nitrogen balance determination in Farm A are shown in **Table 4.6**, and the nitrogen balance, expressed in total mass per place and year and in percentage of the dietary nitrogen input, is shown in **Table 4.7**.

Table 4.6. *Weekly fresh mass balance and nitrogen content of the N-balance components in Farm A. Fresh mass includes weekly feed consumption, increase of body weight (tissues) and the production of faeces and urine*

Week	Fresh mass (g/animal and week)				N content (g N/kg)			
	Feed	Tissues	Faeces	Urine	Feed	Tissues	Faeces	Urine
1	365.5	235.6	190.6	545	25.7	27.7	9.2	4.7
2	632.8	247.6	420.8	1,041	25.7	27.9	10.0	4.1
3	724.4	248.4	555.8	1,505	25.7	28.1	8.0	3.2
4	797.1	193.5	722.7	1,809	25.7	28.3	8.0	2.5
5	611.3	180.1	616.5	1,873	25.8	28.5	8.5	2.3
Total	*3,131*	*1,105*	*2,506*	*6,773*				

Table 4.7. *Weekly nitrogen balance expressed in mass and percentage*

Week	N balance (g N/animal)				N balance (% of N intake)				
	Feed	Tissues	Faeces	Urine	Feed	Tissues	Faeces	Urine	Rest
1	9.38	6.54	1.76	2.56	100.0	69.7	18.7	27.3	-15.7
2	16.27	7.26	4.21	4.27	100.0	44.6	25.9	26.2	3.3
3	18.61	7.97	4.45	4.82	100.0	42.8	23.9	25.9	7.4
4	20.48	6.33	5.78	4.52	100.0	30.9	28.2	22.1	18.8
5	15.76	5.51	5.24	4.31	100.0	34.9	33.3	27.3	4.5
Total	***80.50***	***33.60***	***21.44***	***20.48***	***100.0***	***41.7***	***26.6***	***25.4***	***6.2***

These results are the mean values for all animals in the eight cages. No significant differences were found between cages for any of the parameters involved in the nitrogen cycle.

To produce one kilogram of rabbit tissue, 2.83 kg of feedstuff were needed, 2.27 kg of faeces were excreted and 5.74 L of urine were produced. A small percentage of feed was wasted by animals and collected together with the faeces in the mesh, but in this study this component of the balance was directly assigned to faeces production. Finally, the term *Rest* includes the proportion of the balance that is not accounted for, and corresponds to losses of nitrogen from the collecting system and to inaccuracies in the determination of the balance components.

In **Table 4.7** it can be seen that efficiency in nitrogen conversion by animals decreases as the animal grows, with an average value of 41%. Faeces and urine correspond to approximately one-fourth of the nitrogen intake, and there is a small remainder (6.2%) which could not be explained with the other components, corresponding to losses in the manure collecting system, volatilisation of manure or sampling errors. Furthermore, an uncertainty component related to tissue composition exists, since animal breeding involves a slight increase in meat content.

On a yearly basis, considering a five-week cycle and a sanitation period of one week, values of the nitrogen cycle are those shown in **Figure 4.5.** The excreted nitrogen is approximately 0.4 kg per place and year, which slightly lower than the value obtained in a previous work shown in **Figure 4.2** (Calvet *et al.*, 2006) and also lower than the 0.6 kg N per place and year proposed for the Italian greenhouse gas emission inventory (APAT, 2005).

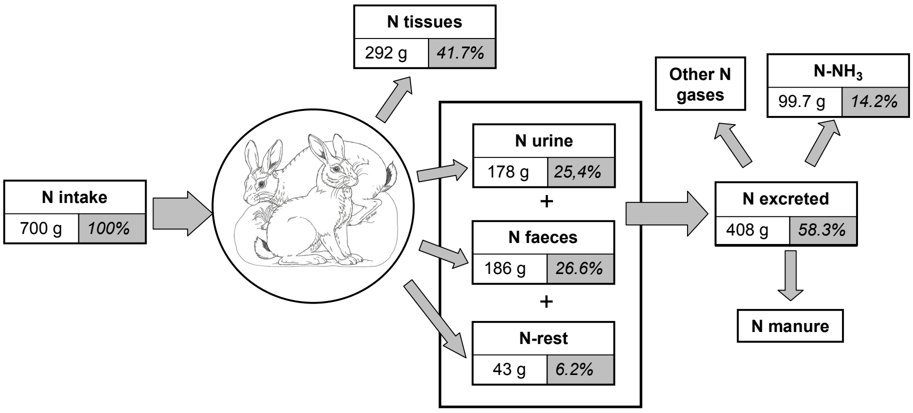


Figure 4.5. *Nitrogen cycle in Farm A expressed in grams of N per place and year and percentages of total nitrogen intake*

The nitrogen excretion estimated in this study is lower than the value obtained by Maertens *et al.* (2005), who carried out a theoretical balance in a commercial farm and found an annual nitrogen excretion of 0.658 kg per fattening place and year, based on the assumption of 7 batches per year and a slaughter weight of 2.5 kg. Differences could be explained by the lower slaughter weight in the present study, but results confirm that nitrogen excretion by fattening rabbits can be established between 400 and 600 grams of N per place and year.

4.3.2. Environmental parameters

Figure 4.6 shows the outdoor temperatures and ventilation rates in each experiment. In summer, fans worked almost continuously in order to control indoor temperatures; in winter, ventilation rates were lower. Ventilation flows in the building for reproductive does were higher than those in the fattening building because of the higher live mass corresponding to a place of a reproductive doe.

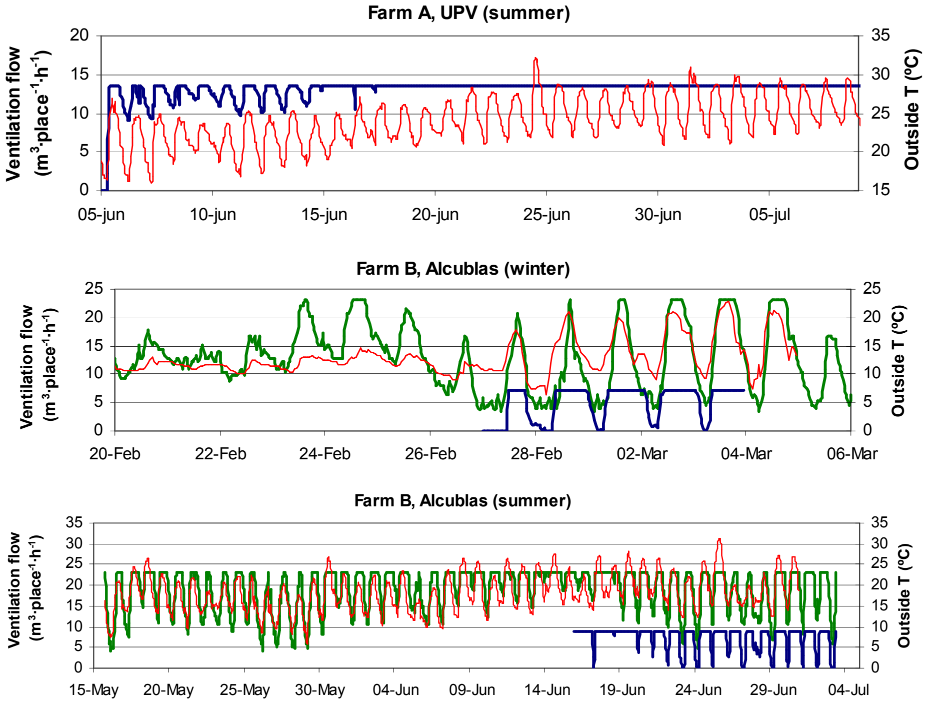


Figure 4.6. *Calculated ventilation rates in the five experiments for fattening rabbits (——) and reproductive does (——), and measured outdoor temperatures (——)*

Figure 4.7 shows the evolution of the measured values of gas concentrations in the five experiments. In all cases, the measured concentrations were lower than the maximum recommended concentrations for animals (CIGR, 1992), which are 3,000 ppm for CO_2 (5,400 $mg{\cdot}m^{-3}$) and 20 ppm for NH_3 (13.8 $mg{\cdot}m^{-3}$). Methane and nitrous oxide concentrations were very similar to outdoor concentrations.

The ammonia concentrations measured in the different experiments were similar to those obtained in previous research, and varied between 2 and 10 $mg{\cdot}m^{-3}$ (see **Table 4.2**). However, carbon dioxide and nitrous oxide concentrations were higher than those obtained by Michl and Hoy (1996), which ranged from 575 to 685 ppm, and from 0.25 to 0.32 ppm, respectively. A wide range of gas concentrations was found in this study, and this was mostly caused by the highly variable ventilation flows in the buildings (see **Figure 4.6**).

A failure in the photoacoustic monitor caused the interruption in measuring gas concentrations in the experiment in Farm B on the 4th of March, and that is the reason why the experiment had to be interrupted at this moment.

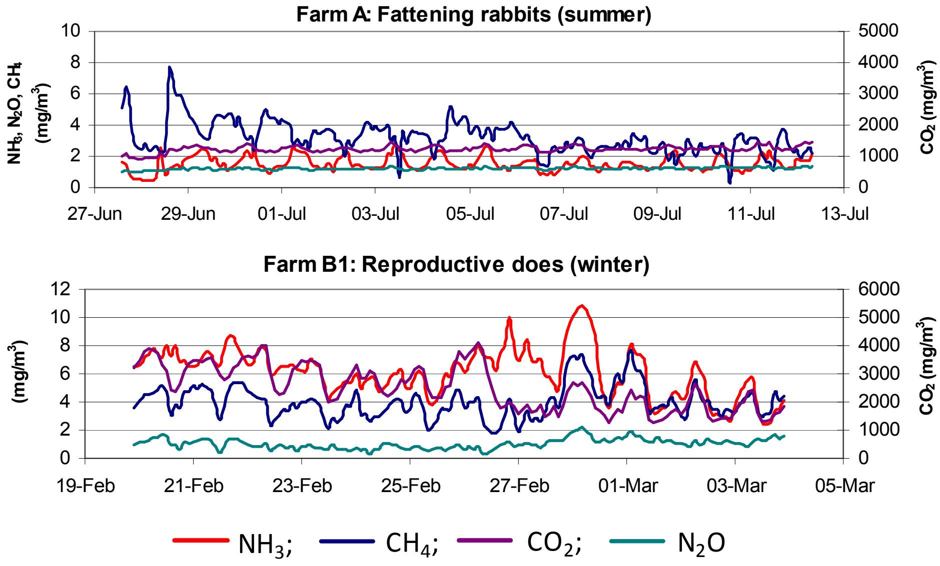
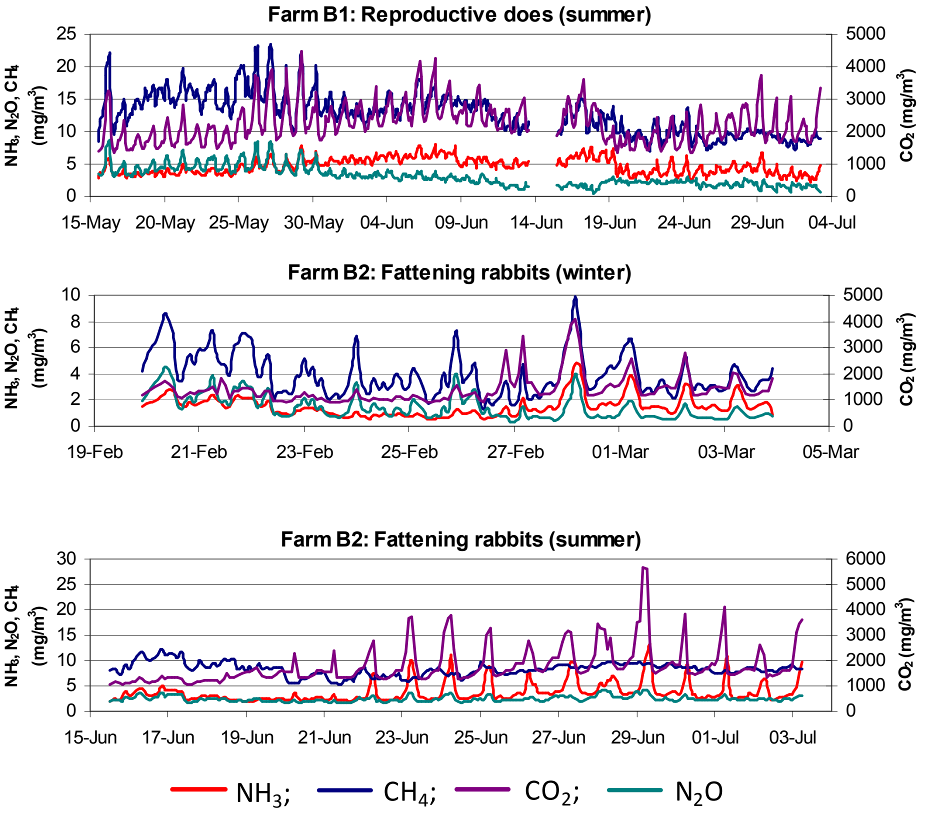


Figure 4.7. *Indoor gas concentrations in each experiment on rabbit farms*


Farm B1: Reproductive does (summer)

Farm B2: Fattening rabbits (winter)

Farm B2: Fattening rabbits (summer)

Figure 4.7 (continued) *Indoor gas concentrations in each experiment on rabbit farms*

4.3.2. Gas emissions

Average daily variations in emission rates in Farms A, B1 and B2 are shown in **Figure 4.8**, **Figure 4.9** and **Figure 4.10**, respectively. A clear daily pattern was found in Farm *A* for CO_2, NH_3 and CH_4 emissions. N_2O emissions, however, were almost constant and near the threshold concentrations. A peak in emissions was identified at 10 a.m. and the lower emissions were found in the afternoon.

This pattern is almost opposite the daily variation of temperature, but it is consistent with the usual daily variation of rabbit activity, considering that they are twilight animals.

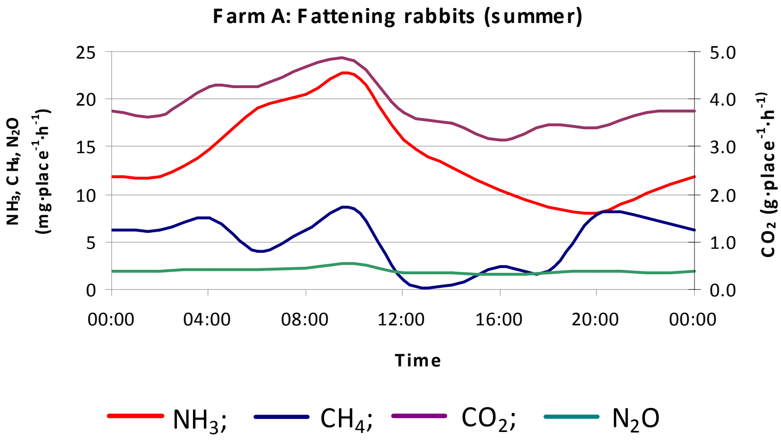


Figure 4.8. *Daily variation of gas emission rates for fattening rabbits in Farm A (UPV, summer)*

The daily variation of emissions in reproductive does in Farm B in Alcublas (**Figure 4.9**) followed a very similar pattern as these obtained in Farm A for CO_2, but in the case of ammonia, this pattern was opposite: a maximum was found coinciding with the early afternoon recordings.

Ammonia emissions in winter were higher than in summer, whereas carbon dioxide emissions were slightly lower. Nitrous oxide and methane emissions were very low and almost constant in winter, but during the summer they were comparable to ammonia emission rates.

For fattening rabbits in Farm B2, the daily variation in summer and winter were different and followed no clear pattern. Negative values for methane and nitrous oxide emissions were also obtained. The interpretation is the uncertainty in the measurement, which makes possible measured negative results when real values are very near zero.

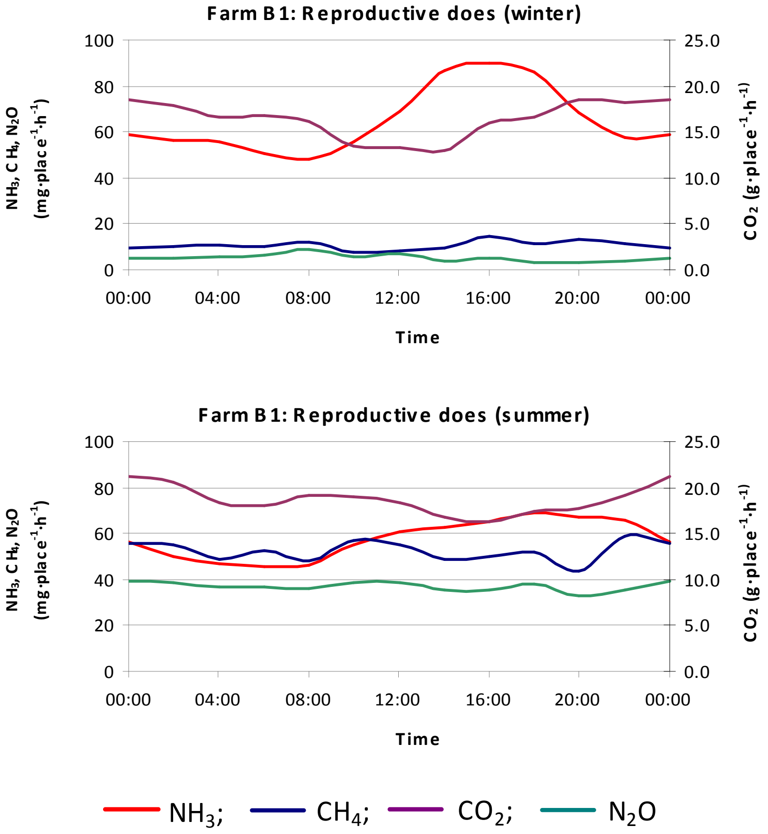


Figure 4.9. *Daily variation of gas emission rates for reproductive does in Farm B1 (Alcublas)*

Average emission factors are provided in **Table 4.8** for fattening rabbits and in **Table 4.9** for reproductive does. Different measurement units are provided in order to make comparisons with other results easier.

Ammonia emissions from rabbits were similar in summer experiments A and B2, and these were very similar to those reported by Hol *et al.* (2004), who found an average emission rate between 130 and 170 grams of ammonia per place and year.

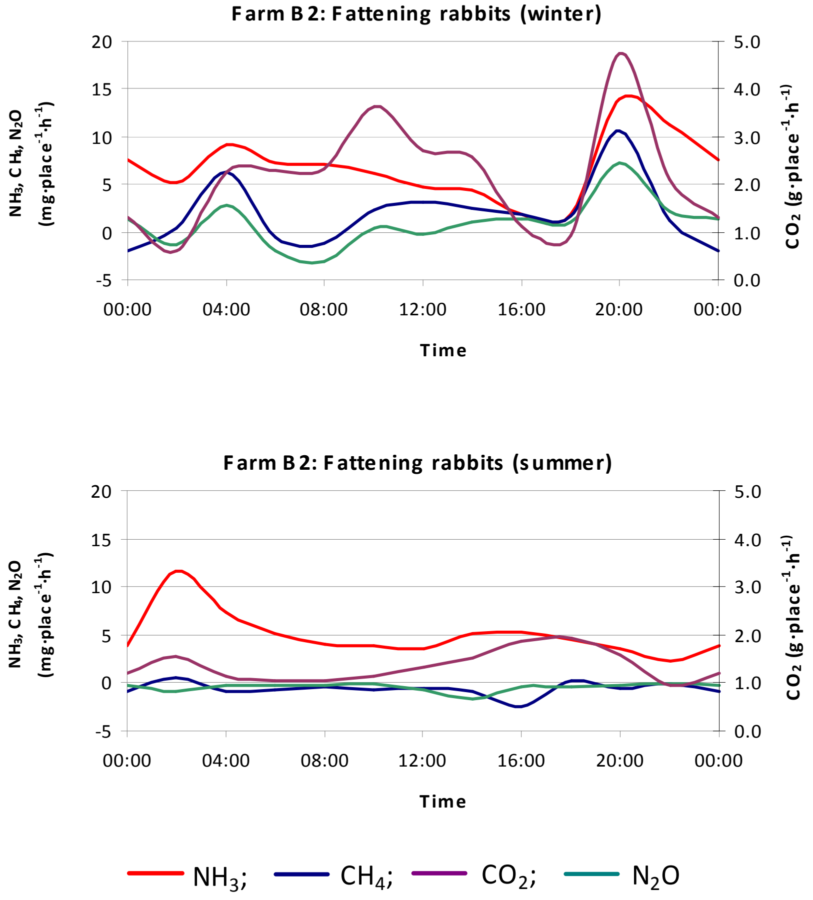


Figure 4.10: *Daily variation of gas emission rates for fattening rabbits in Farm B2 (Alcublas)*

These results also confirm a previous measurement of 160 grams of ammonia per place and year under very similar conditions (Calvet *et al.*, 2006). In winter, the measured results were considerably lower, very near the range proposed by Hol *et al.* (2004) in an autumn experiment, yet higher than the 30 grams per place and year obtained previously under similar conditions (Calvet *et al.*, 2006). In the winter experiment, it must be considered that only the first four days of the fattening period were measured, and this could explain the differences with summer conditions.

Emission factors used in different countries (see **Table 4.1**) could overestimate ammonia emissions. Comparing to other species of similar weight, ammonia emissions from fattening rabbits fall in the range of those for broiler production (50 to 200 $g\cdot LU^{-1}\cdot d^{-1}$) reported by Koerkamp *et al.* (1998) resulting from a multinational project.

Table 4.8. *Average measured gas emissions for fattening rabbits and estimated uncertainties, expressed as standard uncertainties and credibility intervals*

		$g\cdot place^{-1}\cdot year^{-1}$ ($kg\cdot place^{-1}\cdot year^{-1}$ for CO_2)			
		NH_3	CO_2	CH_4	N_2O
A	Mean	121	33.8	44	17
	u	*10*	*3.3*	*17*	*10*
	95% CI	*101 – 142*	*27.6 – 40.4*	*10 – 78*	*-3 – 38*
$B2_{wint}$	Mean	61.7	20.8	20	-7.2
	u	7.1	3.6	10	8.4
	95% CI	*48.1-76.0*	*14.0 – 28.1*	*0 – 40*	*-23.9 – 9.2*
$B2_{summ}$	Mean	138.4	37.8	-14	-5
	u	9.1	3.3	8	4
	95% CI	*120.6 – 156.5*	*32.0 – 44.8*	*-31 – 1*	*-3 – 9*
		$g\cdot LU^{-1}\cdot d^{-1}$ ($kg\cdot LU^{-1}\cdot d^{-1}$ for CO_2)			
		NH_3	CO_2	CH_4	N_2O
A	Mean	139	38.7	51	8
	u	*12*	*3.8*	*20*	*5*
	95% CI	*116 – 163*	*31.5 – 46.2*	*12 – 90*	*-1 – 17*
$B2_{wint}$	Mean	96	32.4	31.2	-11
	u	*11*	*5.5*	*16*	*13*
	95% CI	*75 – 119*	*21.4 – 43.4*	*-1 – 63*	*-37 – 15*
$B2_{summ}$	Mean	189	47.5	-24	-10
	u	*12*	*3.0*	*13*	*9*
	95% CI	*164 – 214*	*41.7 – 53.6*	*-51 – 2*	*-27 – 8*

The same pattern is followed for carbon dioxide emissions, although no previous studies were found to compare this production rate. Regarding methane and nitrous oxide, high uncertainties occur, and in some cases negative values were found. This is because the measured emission rates are very near the precision of the whole measuring system, and therefore clear conclusions cannot easily be drawn. Methane emissions are about 20 grams per place and year, whereas nitrous oxide emissions can be considered negligible. Again, the countries considering rabbit emissions reported slightly higher emission rates than those obtained in this study (see **Table 4.3**).

Table 4.9. *Average measured emissions for reproductive does and estimated uncertainties, expressed as standard uncertainties and credibility intervals*

		$g \cdot place^{-1} \cdot year^{-1}$ ($kg \cdot place^{-1} \cdot year^{-1}$ for CO_2)			
		NH_3	CO_2	CH_4	N_2O
$B1_{wint}$	Mean	575	141	94	-33
	U	*49*	*13*	*13*	*9*
	95% CI	*478 – 672*	*117 – 167*	*69 – 121*	*-51 – -16*
$B1_{summ}$	Mean	500	182	453	93.5
	U	*43*	*15*	*41*	*8.1*
	95% CI	*416 – 585*	*152 – 211*	*374 – 532*	*77.6 – 109.5*
		$g \cdot LU^{-1} \cdot d^{-1}$ ($kg \cdot LU^{-1} \cdot d^{-1}$ for CO_2)			
		NH_3	CO_2	CH_4	N_2O
$B1_{wint}$	Mean	262	65	43	-15.2
	U	*22*	*6*	*6*	*4.1*
	95% CI	*217 – 307*	*53 – 76*	*31 – 55*	*-23.5 – -7.0*
$B1_{summ}$	Mean	342	125	310	64.1
	u	*29*	*12*	*28*	*5.5*
	95% CI	*283 – 401*	*102 – 150*	*254 – 366*	*52.9 – 75.2*

Ammonia emissions from reproductive does in winter and summer turned out to be very similar, considering the relatively high uncertainties obtained. These values are lower than those obtained by Hol *et al.* (2004), and much lower than those used in some emission inventories (see **Table 4.1**). Methane emissions were significant in contrast to the results obtained for fattening rabbits, and were similar to the previous estimations of Langer (2002). The emission of nitrous oxide was variable: no emission was found in winter, whereas in summer the measured value was 93 grams of N_2O per place and year.

4.4. Conclusions

In this study, gas emissions from two commercial rabbit farms were studied, including the breeding and the fattening phase. Furthermore, a nitrogen balance was performed in a fattening cycle. The results obtained here serve as a solid base to propose emission factors to be used in emission inventories.

Nitrogen excretion for fattening rabbits of 1.8 kg at slaughter is 0.4 kg per place and year, although higher excretion (about 0.6 kg per place and year) is expected in rabbits with a final weight about 2.5 kg, according to literature.

Gas concentrations in the measured farms lie under the maximum recommended thresholds for animal welfare and human health, except in particular operations such as manure removal. However, concentrations can be strongly affected in different farms by the ventilation programme.

Gas emissions follow a daily pattern apparently related to daily variation in animal activity and ventilation rates. More effort should be made to relate carbon dioxide production to animal activity, since rabbit activity patterns are completely different from most other farm animals. Further data are crucial to properly estimate ventilation rates using the carbon dioxide balance method.

Preliminary emission factors can be derived from this study. For fattening rabbits, measured ammonia emissions were 121 and 138 g per place and year in summer conditions, and 62 g per place and year in winter. Further measurements must be carried out to confirm these results, especially in winter. For reproductive does, the obtained values were 575 and 500 g per place and year in summer and in winter, respectively.

Carbon dioxide production in fattening rabbits is between 34 and 38 kg per place and year in summer, whereas no representative results were obtained in winter. For reproductive does carbon dioxide production was found to range between 141 and 182 kg per place and year. Methane production in fattening rabbits was negligible, whereas for reproductive does the wide range obtained (100 – 450 g per place and year) requires further studies. In all cases, nitrous oxide emissions were negligible; therefore, the emission factor for rabbit houses should be zero.

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Chapter 5

Gas emissions in a Mediterranean broiler farm

Gas emissions in a Mediterranean broiler farm

Abstract

Gas emissions from broiler production have been the subject of much research in many countries, and much information on average values and mitigation techniques is available. Nevertheless, there is one main constraint when applying the findings to Spanish conditions: there is little experimental information which is relevant under local management and environmental conditions. So, in this study, ammonia, carbon dioxide, methane and nitrous oxide concentrations and emissions were measured in a 130x14 m building in a commercial broiler farm located in Castellón (Spain), using a mass balance in the air. The gas concentration was measured using a photoacoustic gas monitor, whereas the ventilation flow was evaluated by controlling the operation status of each fan. Two complete rearing periods were studied in different conditions, the first one in summer (July – August 2006), and the second in winter (December 2006 – January 2007). Uncertainty was calculated and reported for all emission data, using numerical methods (Monte Carlo). Calculated emissions expressed per place and year were 97 and 87 g NH_3, 19.50 and 19.53 kg CO_2, 1.75 and 8.88 g CH_4, and 9.4 and 11.2 g N_2O for summer and winter, respectively. The uncertainty, expressed as standard deviations of the mean values, was calculated to be between 7 and 10% of the reported value for ammonia and carbon dioxide. Relative uncertainties were higher in methane and nitrous oxide estimates.

Keywords: broiler, poultry, gas emissions, ammonia, carbon dioxide, methane, nitrous oxide.

5.1. Introduction

5.1.1. Overview

Intensive rearing of chickens for meat production accounts in Spain for 130 million places and 1,047,580 metric tons of meat production in 2005, being the second most important producer in the European Union after the United Kingdom (FAOSTAT, 2007).

Typical Spanish intensive broiler farms are transversal mechanically ventilated; they use different bedding materials, particularly rice hulls and wood shavings, according to the availability and prices of these products. As a consequence of the different market demands, rearing cycles are usually long (up to 7 weeks and animals about 2.6 kg in final weight) in comparison to those in other European countries (5 to 6 weeks and 2 to 2.2 kg in weight). Litter is always removed at the end of the cycle in contrast to the usual reuse of litter in some countries, for example in the U.S.A.

It must be emphasised that much heterogeneity is found in experimental procedures for estimating gas emissions for presenting the results, in such a way that comparisons are usually difficult. For this reason, commonly accepted methodologies and comprehensive descriptions of the experiments must be used to report this information (Koerkamp *et al.*, 1998).

Uncertainty analyses are also necessary to correctly report the emission estimates. This kind of analysis is acknowledged as crucial in the reporting of gas emission inventories (IPCC, 2001), but in the reporting experimental gas emission estimates, there is no commonly accepted procedure given its complexity. Thus, many studies offer no explicit information about the quality (uncertainty) of the experimental results, but this should not continue to be the common practice in a research area subjected to considerably high uncertainty and temporal and spatial variability, as explained in chapter 2.

5.1.2. Ammonia emissions in broiler production

Ammonia is produced in broiler facilities due to the biological breakdown of uric acid, usually within a few days at normal conditions in broiler facilities, according to the process described by Carlile (1984). Microorganisms such as bacteria, fungi and actinomycetes are involved in this process.

Extensive research has been done on ammonia release from broiler buildings attending to its distinct effects: the environmental impact (Hayes *et al.*, 2006; Lacey *et al.*, 2003; Redwine *et al.*, 2002; Siefert *et al.*, 2004; Wathes *et al.*, 1997; Zhu *et al.*, 2000), the negative effects on human health (Hinz and Linke, 1998; Koerkamp *et al.*, 1998), the loss of nitrogen as a nutrient (Coufal *et al.*, 2006; Guiziou and Béline, 2005), or the negative effects on broiler meat production and performance (Homidan *et al.*, 2003; Kristensen and Wathes, 2000; Quarles and Kling, 1974; Reece *et al.*, 1980; Reece *et al.*, 1981; Robertson *et al.*, 1990; Wathes *et al.*, 2002; Xin *et al.*, 1996). **Table 5.1** summarizes the reported ammonia emissions obtained from the literature.

Table 5.1. *Experimental data on ammonia emissions from broiler production*

Country	Reported value	Unified value $g\ NH_3 \cdot kg\ meat^{-1}$	Reference
UK	$9.2\ g\ NH_3\ h^{-1} LU^{-1}$	13.2	Wathes *et al.* (1997)
UK	$16.6\ kg\ NH_3\ LU^{-1} y^{-1}$	4.0	Demmers *et al.* (1999)
UK	$3.5 – 3.9\ g\ NH_3 \cdot bird^{-1}$	1.8 – 2.0	Robertson *et al.* (2002)
UK	$8.3\ g\ NH_3 \cdot h^{-1}\ LU^{-1}$	10.0	Koerkamp *et al.* (1998)
Holland	$4.2\ g\ NH_3 \cdot h^{-1}\ LU^{-1}$	5.6	
Denmark	$2.2\ g\ NH_3 \cdot h^{-1}\ LU^{-1}$	4.5	
Germany	$7.5\ g\ NH_3 \cdot h^{-1}\ LU^{-1}$	9.3	
France	$5.74\ g\ N\text{-}NH_3 bird^{-1}$	3.7	Guiziou and Béline (2005)
Ireland	$0.16 - 0.50\ g\ NH_3 \cdot d^{-1} \cdot bird^{-1}$	3.1 – 9.7	Hayes *et al.* (2006)
USA	$11.1\ g\ NH_3 \cdot kg\ prod^{-1}$	11.1	Coufal *et al.*(2006)
USA	$1.18\ g\ N\text{-}NH_3\ animal^{-1} d^{-1}$	18.9	Siefert *et al.* (2004)
USA	$632\ mg\ NH_3 day^{-1} bird^{-1}$	12.9	Lacey *et al.* (2003)
USA	$59\text{-}2105\ g\ NH_3 \cdot h^{-1}$	n.p. (1)	Redwine *et al.* (2002)
USA	$8\text{-}21\ mg\ NH_3 m^{-2} s^{-1}$	n.p. (1)	Zhu *et al.* (2000)
Spain	$421\ g\ NH_3\ pl^{-1} year^{-1}$	28.1	MAPA (2004) (2)

(1) Conversion not possible with the data provided in the corresponding source

(2) Emission factor used for the Spanish EPER register based on literature data, which also includes manure management

High variability can be found in all reported data, both in the values and in the units employed by different authors. Furthermore, numerous factors affect ammonia production (Elliott and Collins, 1982; Patterson and Adrizal, 2005): litter material, temperature, litter humidity, ventilation flow and abatement techniques. It is therefore extremely difficult to determine a representative emission factor for a certain region, and in all cases, an estimation of the uncertainty of the reported value should be provided.

5.1.3. Greenhouse gas emissions in broiler production

Broiler houses are not considered to be a significant source of methane, since enteric fermentation processes in monogastrics are reduced and anaerobic fermentation of manure is very low given the high aeration of the most commonly used bedding materials. Crutzen *et al.* (1986) provided a comprehensive list of methane emission factors from enteric fermentation, but poultry were absent from the list, and based on these estimates, the International Panel on Climate Change (IPCC) did not consider methane emissions from poultry production in the National Emission Inventories (IPCC, 1997).

Nevertheless, there are a few experimental studies indicating the order of magnitude of these emissions. Methane emission from enteric fermentation in poultry was evaluated by Wang and Huang (2005) using an environmental chamber, and they found an average emission factor of 15.87 mg CH_4·bird produced^{-1}. Wathes *et al.* (1997) estimated methane emissions from poultry houses in 0.25 mg g·LU^{-1}h^{-1} (approximately 400 mg CH_4·bird produced^{-1}). Guiziou and Béline (2005), however, found no significant methane emissions from broilers using the same method.

Additionally, nitrous oxide is barely emitted from broiler houses, since the biological processes leading to its production do not occur in the litter during the growing period. Wang and Huang (2005) measured nitrous oxide from broilers, finding a nearly negligible emission factor: 0.03 mg N_2O·bird produced^{-1}. Wathes *et al.* (1997) estimated nitrous oxide emissions in about 0.7 g·h^{-1}·LU^{-1} (approximately 1 g N_2O·bird produced^{-1}), probably originating in litter reactions.

CO_2 production from animals has been used as a trace gas to indirectly determine the ventilation flow, according to a commonly accepted procedure (CIGR, 2002). However, direct measurements of CO_2 emissions are usually not reported, since this gas is not considered a net pollution on the environment. CO_2 production by broilers has been reported to be proportional to the heat production, and thus to the metabolic weight of the animals, and it is also affected by the temperature, according to Equation 5.1 (adapted from CIGR, 2002).

$$m_{CO2} = \rho_{CO2} \cdot 10.62 \cdot LW^{0.75} F_T \cdot 0.185 \qquad \textit{(Equation 5.1)}$$

Where:

m_{CO2}: Hourly carbon dioxide production (g·animal^{-1}·h^{-1})

ρ_{CO2}: CO_2 density (g/m^3), affected by temperature and atmospheric pressure

F_T: Correction for temperature (see chapter 6)

LW: live weight of animals (kg)

A similar procedure was proposed by the German DIN 18910 (1992 Edition), establishing the CO_2 emissions from broilers according to Equation 4.2. (Hörnig *et al.*, 2002):

$$m_{CO2} = 3.0153 \cdot LW^{0.7676} \qquad \textit{(Equation 5.2)}$$

This equation is, however, incomplete because it does not take into account the influence of the ambient temperature on the respiratory rate. Furthermore, it underestimates the values obtained with Equation 5.1, when the usual temperatures in broiler farms are taken into account (**Figure 5.1**). This underestimation may be caused by increased broiler growth rates between the two reported references, given improvements in animal genetics.

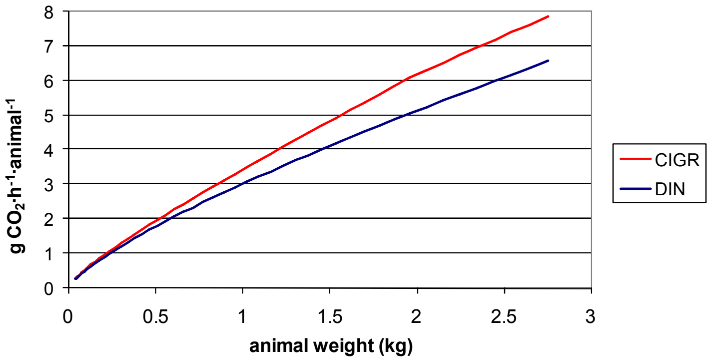

Figure 5.1. *Comparison of carbon dioxide production rates according to two different models: DIN 18910 (1992) and CIGR (2002)*

These two predictions of carbon dioxide refer only to animal respiration, and possible production from litter is not considered. On the other hand, daily carbon dioxide production rates vary due to changes in animal activity, which is not taken into account in these curves (CIGR, 2002).

5.1.4. Research objectives

The main objective of this study was to obtain consistent data on gas emissions (NH_3, CO_2, CH_4 and N_2O) in a commercial broiler farm under the typical conditions in Spain, and then, to examine the parameters affecting the emissions, particularly the seasonal effect.

5.2. Materials and Methods

5.2.1. Description of the farm

Gas emissions were measured in a commercial, mechanically-ventilated broiler farm located in Villareal (Castellón, Spain, 39°57'36"N 0°08'49"W, 90 m above sea level) in summer 2006 and winter 2007. The building measured 130 x 14 meters and housed approximately 21,000 birds. This farm is representative of the commercial farms in this region. It has 16 lateral fans: nine of them larger ($Q_N = 34,956$ $m^3 \cdot h^{-1}$) than the other seven ($Q_N = 12,750$ $m^3 \cdot h^{-1}$). The ventilation rate was controlled by a commercial control system (Tuffigo®) depending on animal age and environmental conditions.

The summer experiment started with 10,000 male and 10,100 female chicks on 20th July 2006 and ended on 4th September 2006, with a cycle length of 48 days. Approximately 20% of the 42-day-old chickens were removed on 28th August. Mortality during the growing period was 5.14%, and the final production was 19,067 animals and 46,420 kg (2.43 kg/bird), with a feedstuff consumption of 84,913 kg and a conversion rate of 1.83.

The winter experiment started on 15th December 2006 with 12,000 male and 12,000 female broiler chicks and ended on 31st January 2007 (49 day cycle). Approximately 15% of the 42-day-old chickens were removed on 24th January. Mortality during the growing period was 3.28%, and the final production was 23,212 animals and 62,534 kg (2.69 kg/bird), with a feedstuff consumption of 114,000 kg and a conversion rate of 1.82.

Rice hulls (approximately 8-10 cm deep and 4 kg·m^{-2}) were used as bedding material, and the litter was removed at the end of the cycle, establishing a sanitation period between 2 and 3 weeks.

5.2.2. Measuring emissions

Gas emissions are calculated by means of a gas balance method in the volume determined by the building, according to Equation 5.3.

$$E = \left(C_{outlet} - C_{inlet}\right) \cdot V \qquad \text{(Equation 5.3)}$$

Where:

E: Emission (mg·h^{-1})

C: Inlet and outlet gas concentration (mg·m^{-3})

V: Ventilation flow in the building (m^3·h^{-1})

The ventilation flow was calculated following the methodology described in chapter 3; both calibration curves and operating times of each fan were determined and hourly ventilation flows for the whole building were obtained.

Concentrations of CO_2, N_2O, NH_3, CH_4 and H_2O were measured using a photoacoustic multi gas monitor (INNOVA 1412) equipped with a gas multiplexer that allowed sequential measurement in 8 different points until 100 m away from the measurement unit, in a 2-hour sequence (15 minutes for each measurement). As shown in **Figure 5.2**, four sampling points were placed next to the extraction fans of the building at a height of 1.2 m to determine exhaust gas concentrations, two at the air inlet openings for the characterization of outside air, and the other two measurement points were placed in the middle of the building (1.2 m height), in order to obtain further data on the distribution of gas concentrations.

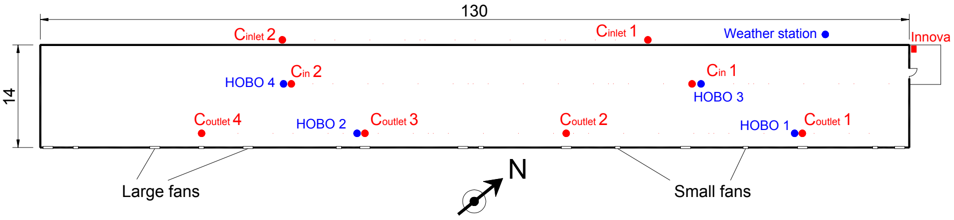

Figure 5.2. *Distribution of the farm: location of the gas concentration sampling points and environmental monitoring systems*

5.2.3. Measuring related parameters

The temperature and relative humidity were continuously measured both indoors and outdoors, using four data loggers (HOBO H8-004-002 Onset Computer Corp., Pocasset, Mass.) and a weather station (HOBO Weather Station), respectively. The location of these instruments is detailed in **Figure 5.2**.

5.2.4. Data analysis

An uncertainty analysis was performed in three steps as explained in chapter 2 and according to JCGM (2006): formulation, propagation and summarizing.

The formulation of the model is performed according to **Figure 2.3**, and the probability density functions (PDFs) were assigned as shown in **Table 2.2**.

For the propagation stage, numerical methods (Monte Carlo) were used to propagate the PDFs. The software used for the analysis was RiskAMP Monte Carlo Add-In Library version 2.70 for Excel (Structured Data, 2005).

5.3. Results and discussion

5.3.1. Gas concentrations

Measured gas concentrations during the two complete cycles are represented in **Figure 5.3**. In experiment 2, measurements started on day 7 of the cycle due to failures in the gas analyzer.

In winter conditions, gas concentrations are normally higher than in summer, due to the reduced ventilation flows. In both cases, a daily variation pattern was observed as a result of the variation in ventilation flow, and gas concentrations were higher at night than during the day.

Ammonia concentration was normally under the threshold values recommended by CIGR (1992) for animal welfare and human well-being (25 ppm = 17.5 $mg \cdot m^{-3}$), and this threshold was reached only on cold winter nights. Ammonia concentration was almost negligible until the 10th and 20th day of the fattening period in winter and summer, respectively.

Carbon dioxide and nitrous oxide followed a very similar pattern, but they posed no risk for human or animal health. Methane concentration was normally below 5 $mg\ m^{-3}$, whereas nitrous oxide was almost always below 1 $mg \cdot m^{-3}$.

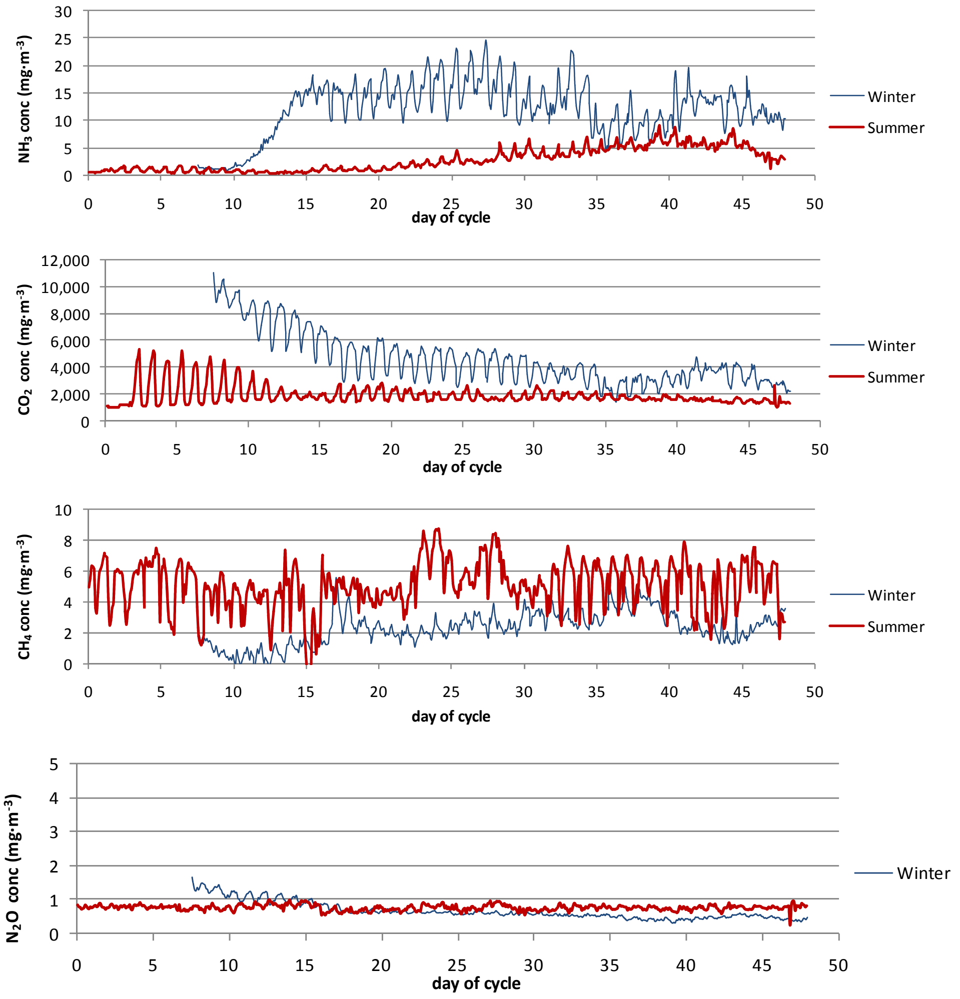

Figure 5.3. *Evolution of the indoor NH_3, CO_2, CH_4 and N_2O concentrations during the two experiments*

5.3.2. Gas emissions

Measured gas emission rates and accumulated emissions (NH_3, CO_2, CH_4 and N_2O) for the two complete cycles are represented in **Figure 5.4.**

The total ammonia emission was very similar in summer and winter, although the temporal pattern during the cycle was completely different. In winter, emissions were high and almost constant from day 25 of the growing period.

In summer, however, significant emissions started later (about day 35). This is similar to results reported by Guiziou and Béline (2005), who found a significant increase in ammonia emission on day 30 in winter conditions. The explanation for this difference is the state of the litter: in winter, lower ventilation flows mean the litter is wet early in the cycle and biological reactions leading to ammonia production occur. In summer, however, the litter is dry until later in the cycle, since the ventilation flows are high, and the main biological activity in the litter occurs at the end of the rearing period.

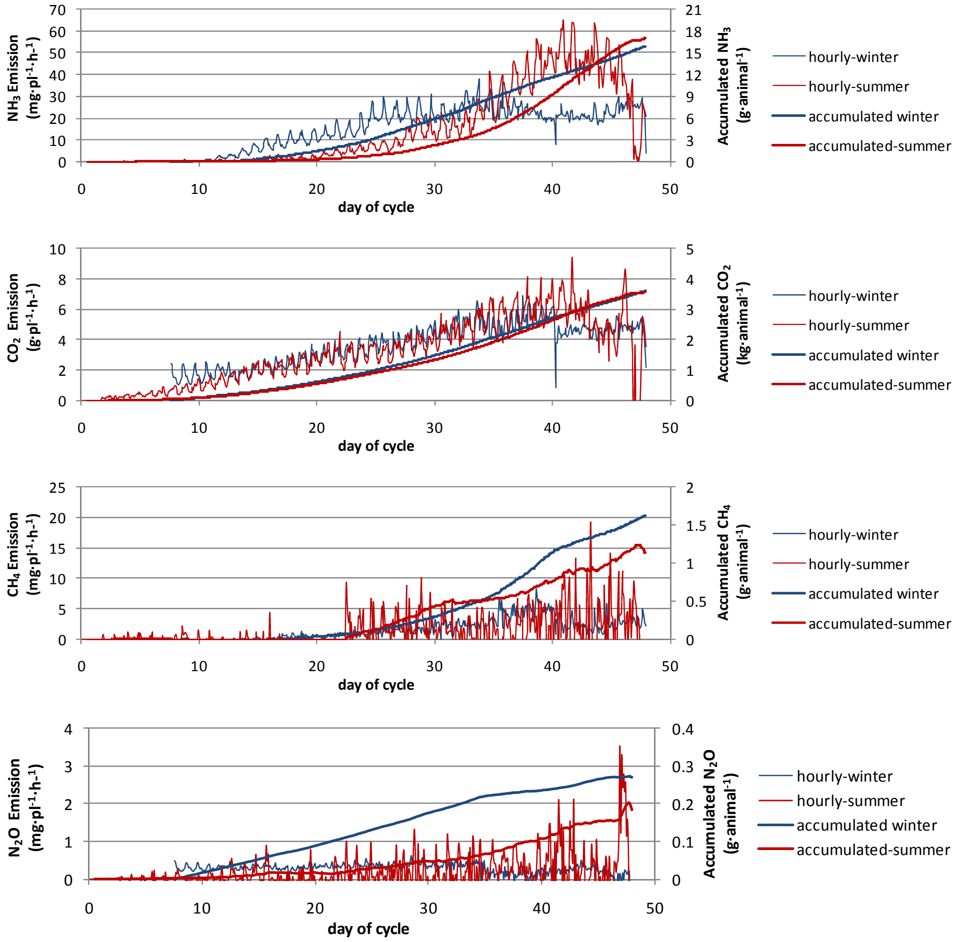

Figure 5.4. *Evolution of NH_3, CO_2, CH_4 and N_2O emission rates and accumulated emission in summer and winter, expressed per animal place*

Carbon dioxide emission values and temporal patterns during the cycle were very similar in winter and summer (3.58 kg $CO_2 \cdot bird^{-1}$). This is logical, since carbon dioxide is mainly produced by the birds in their breathing, depending on animal activity and temperature, and these parameters are quite independent from outside environmental conditions because of the strict environmental control in broiler farms.

For methane and nitrous oxide, winter emissions were found to be slightly higher than in summer. For both gases, emission was found to be about two grams per animal produced, which is higher than those reported in the literature.

5.3.3. Average emissions and uncertainties

The results of the average emission factors and uncertainty analysis performed for each gas are summarised in **Table 5.2.** Three different units are reported in order to facilitate comparisons: emission per animal produced, emission per place and year, and emission per kg of animal produced. Although some of these values are calculated on a yearly basis, the season in which they are obtained must not be ignored.

Uncertainty is expressed as a standard deviation and as a 95% confidence interval, and in these two experimental periods constituted between 7 and 10% of the reported value for ammonia and carbon dioxide, and was mainly caused by the uncertainty in measuring the ventilation flow, as explained in chapter 2.

Ammonia emission during summer was slightly higher than in winter. Both values are within the range provided in **Table 5.1**, but they are considerably lower than the average emission factor given in Spain for broiler production. The values obtained are also lower than a previous rough estimation of 170 g NH_3 per place and year for a Spanish broiler farm in summer conditions (Calvet *et al.*, 2007).

Total carbon dioxide production is similar to the estimation of the CIGR methodology, according to Equation 5.1 (3.79 kg $CO_2 \cdot bird^{-1}$) and the DIN procedure (3.26 kg $CO_2 \cdot bird^{-1}$). In brief, approximately 1.4 kg CO_2 is produced to obtain 1 kg of meat.

Methane and nitrous oxide emissions are less than 1 g per bird produced, and these estimations have high uncertainties because the measured concentrations are very near the measuring threshold of the gas monitor. These results confirm that methane emissions from broilers are very low (< 1 kg CH_4·LU^{-1}·y^{-1}) in comparison to those emitted by other species such as pigs (12.5 kg CH_4·LU^{-1}·y^{-1}) or cattle (60 – 90 kg CH_4·LU^{-1}·y^{-1}) according to the Spanish methodology for the estimation of gas emissions for the National Emission Inventory (Torres *et al.*, 2006).

Table 5.2. *Average measured gas emissions and estimated uncertainties in summer (S) and winter (W)*

		g·bird^{-1}			
		NH_3	CO_2	CH_4	N_2O
S	Mean	17.0	3,580	0.32	1.73
	U	*1.3*	*266*	*0.15*	*0.13*
	95% CI	*14.6 – 19.6*	*3,075 – 4,118*	*0.03 – 0.63*	*1.48 – 1.99*
W	Mean	15.9	3,584	1.63	2.06
	U	*1.1*	*245*	*0.11*	*0.14*
	95% CI	*13.8 – 18.1*	*3,101 – 4,068*	*1.42 – 1.84*	*1.78 – 2.34*
		g·place^{-1}·year^{-1}			
		NH_3	CO_2	CH_4	N_2O
S	Mean	97.2	19,503	1.75	9.40
	U	*7.7*	*1,490*	*0.84*	*0.72*
	95% CI	*82.5 – 112.8*	*16,704 – 22,538*	*0.14 – 3.44*	*8.05 – 10.85*
W	Mean	86.9	19,526	8.88	11.21
	u	*6.0*	*1,379*	*0.62*	*0.80*
	95% CI	*75.1 – 98.8*	*16,824 – 22,251*	*7.67 – 10.10*	*9.66 – 12.79*
		g·NH_3·kg^{-1} meat produced			
		NH_3	CO_2	CH_4	N_2O
S	Mean	7.1	1,485	0,13	0,08
	U	*0.9*	*97*	*0.06*	*0.05*
	95% CI	*5.1 – 9.2*	*1,181- 1,643*	*0.01 – 0.22*	*0.00 – 0.17*
W	Mean	5.9	1,334	0.61	0.10
	u	*0.9*	*80*	*0.12*	*0.00 – 0.32*
	95% CI	*4.5 – 6.6*	*1,090 – 1,530*	*0.40 – 0.82*	*0.08*

5.4. Conclusions

The results from these two experiments on gas emissions in a typical Spanish commercial broiler farm indicate that emissions fall in the range of the experimental values obtained for other countries, and this can be explained by the fact that environmental conditions in broiler production are always controlled and tend to be independent from outside conditions.

Gas concentrations are within the recommended thresholds, although they are higher in winter than in summer given the lower ventilation flow. The use of new litter material each cycle determines the ammonia production dynamics, since the microbial reactions leading to ammonia production require the accumulation of water and nitrogen. For this reason, ammonia emissions are mainly produced at the end of the summer cycle, whereas in winter it is more constant throughout the cycle.

Carbon dioxide emissions were quite similar to the values proposed by CIGR and DIN. Nitrous oxide emission was low in comparison to the other gases, and methane production was negligible.

The results obtained have been expressed in distinct units so as to facilitate comparisons with other studies. Furthermore, the uncertainty analysis ensures the quality of the data obtained, in such a way that the results obtained are representative for farms having similar management practices. According to results obtained in this study, the following emission factors can be proposed: 90 g NH_3·place^{-1}·y^{-1}, 19.5 kg CO_2·place^{-1}·y^{-1}, 2-9 g CH_4·place^{-1}·y^{-1} and 9-11 g N_2O place^{-1}·y^{-1}. Methane and nitrous oxide emissions were estimated with high uncertainties, but the measured emissions were low in comparison to other species such as pigs or cattle. For ammonia and carbon dioxide, the uncertainties in the final estimates were lower than 10% of the measured value.

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Chapter 6

The influence of the lighting programme on broiler activity, gas and dust (PM_{10}) production

The influence of the lighting programme on broiler activity, gas and dust (PM_{10}) production

Abstract

Among the factors influencing gas emissions, animal activity is probably the least studied. Animal activity is strongly affected by circadian rhythms and it is altered by the rearing conditions, particularly the management of light and feeding. In this study, a 35-day broiler flock was studied with the following objectives: (1) to measure concentrations and emissions of pollutants (gases and dust), (2) to evaluate numerically the influence of the lighting programme on animal activity, dust and gas production, and (3) to evaluate the suitability of the carbon dioxide balance method proposed by CIGR. This study was conducted in the Research Centre for Animal Production and Technology (FOSVWE) in Vechta (Germany), belonging to the Georg-August-Universität Göttingen. Two daily dark periods of 6 and 4 hours were evaluated in an experimental room with 158 birds divided into 12 groups. A TEOM analyser was used to determine dust concentrations (PM_{10}), whereas gas emissions were measured using a FTIR analyser. Animal activity was determined by direct evaluation of videos, and resulted to be closely related to the light programme. PM_{10} concentration increased linearly with bird weight, and was strongly affected by animal activity. Carbon dioxide production was 4.74 $kg \cdot bird^{-1}$ and varied depending on the metabolic weight of animals and animal activity. Ammonia production was 7.79 $g \cdot bird^{-1}$, whereas methane and nitrous oxide production was negligible. A very good linear relationship was obtained for the CO_2 balance method on a 24-hour basis ($R^2 = 0.99$), but the measured CO_2 production was 1.9 times higher than expected using CIGR default values. Furthermore, the observed animal activity did not directly correspond to the measured carbon dioxide production, and discrepancies were found in the balance on a 30-minute basis.

Keywords: *broiler, animal activity, lighting programme, gas emission, particulate matter, carbon dioxide balance.*

6.1. Introduction

6.1.1. General definitions on animal activity

There are numerous factors which determine the emission of pollutants from livestock and poultry facilities: animal type and age, manure management system, environmental conditions, etc. Animal activity is perhaps the least studied factor, and there are two main reasons for this. Firstly, animal activity can be defined at very different levels, from very detailed (*e.g.* movement of a single muscle) to very generic (*e.g.* eating or drinking). Secondly, the measurement of animal activity is very difficult to record automatically. Animal activity has been monitored in relation to animal welfare and behaviour, usually by direct observation of animals, and according to the research objectives: presence of a certain activity, frequency of occurrence and duration of each activity, the intensity, the timing and the nature of certain behaviours (Fraser and Broom, 1997).

In relation to gas production, animal activity has been studied in order to properly conduct indirect measurements of ventilation flows by means of carbon dioxide balances (Van Ouwerkerk and Pedersen, 1994; CIGR, 2002). Passive infrared detectors (PIDs) have been successfully used to automatically determine animal activity for these purposes, assuming that animal activity is defined as movements, and very good correlations were found for pigs in relation to dust production and the performance of carbon dioxide balances (Pedersen and Pedersen, 1995; Pedersen, 2005).

In broiler production, PIDs were used to compare differences in activity using different feeding systems (Nielsen, 2001), and to study the influence of light in relation to age and feed type (Nielsen *et al.*, 2001). In these studies, a significant influence of light on animal activity (see **Figure 6.1**) and an increase with animal age were reported, but no cross-effect between animal age and light programme was found. In relation to feeding systems, *ad libitum* management showed lower activity than restricted feeding for animals of the same age. However, sensitivity problems were reported in the use of the PIDs caused by the inaccuracy in distinguishing slight movement differences, and to the masking effect caused by increased litter temperature (Nielsen *et al.*, 2001).

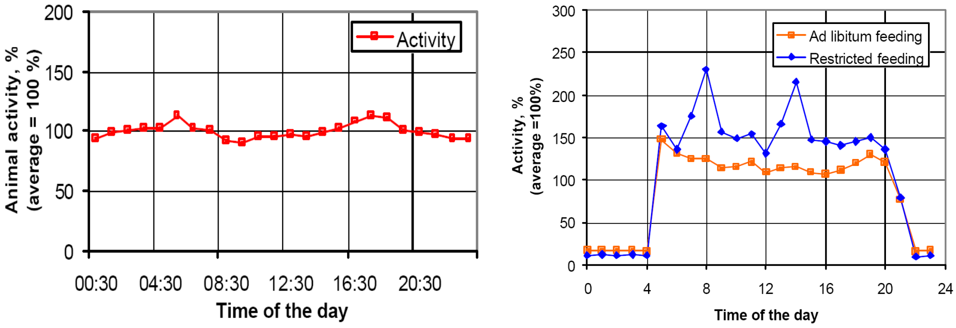

Figure 6.1. *Daily variation in broiler activity in two different lighting programmes: on the left, ad libitum feeding and 24-hour artificial light; on the right, a 16:8 h light:dark programme with different feeding strategies (CIGR, 2002)*

6.1.2. Dust production and animal activity

Dust concentration is strongly affected by environmental conditions, particularly animal activity (affected by the lighting programme), animal age and litter material (Gustaffson, 1997). Dust concentrations in broiler houses have been reported by numerous authors, as summarized in **Table 6.1**. The main dust sources in farms are feed, the animals themselves, faeces and urine, and the bedding material (Aarnink and Ellen, 2007).

Dust fractions are defined and reported in this study according to the European Norm EN 481 (1993). According to this norm, the following particle size ranges are distinguished: inhalable or total dust (particles smaller than 50-100 μm), thoracic or inspirable dust (particles smaller than 10 μm), which is equivalent to the term PM_{10}, and respirable dust (particles smaller than 4 μm), which is equivalent to the term PM_4 (Aarnink and Ellen, 2007).

In an attempt to relate dust concentration, broiler activity and lighting programme, Yoder and Van Wicklen (1988) measured bird activity with a sound level meter, but they found no reliable results. The same authors reported a logarithmic increase in dust with live weight, an average particle diameter of 3.3 to 4.7 μm, and a significant difference between night and light periods.

Hinz and Linke (1998) reported a linear relationship between dust concentration and animal live weight, being the dust affected by temperature and ventilation flow. Redwine *et al.* (2002) found higher concentrations of total suspended particles (TSP) in winter than in summer due to lower ventilation flows, and a linear dependence on bird age. Lacey *et al.* (2003) identified a linear increase in dust emission with bird age, and reported an emission factor of 1.3 g PM$_{10}$ bird^{-1}.

***Table 6.1.** Experimental data on dust concentrations from broiler production*

	Concentration, mg·m^{-3}		Country	Source
	mean	Range		
Inspirable dust	8.9	2.0 – 13.2	England	Conceiçao *et al.* (1989)
	9	8-12	England	Wathes *et al.* (1997)
	-	9.2 – 11.1	Scotland	Al Homidan *et al.*(1998)
	-	1-14	Germany	Hinz and Linke (1998)
	10	9.92 – 10.36	England - Netherlands	Takai *et al.* (1998)
	4	3.83 – 4.49	Denmark - Germany	
	-	1.2 – 8.5	Germany	Elhussein and Van den Weghe (1999)
	-	8.2 - 9	The Netherlands	Ellen *et al.* (2000)
	-	0.73 – 11.39	U.S.A.	Redwine *et al.* (2002)
	-	1.77 – 4.41	Scotland	Al Homidan (2004)
Respirable dust	5.43 (day 28) 9.71 (day 49)		U.S.A.	Willis *et al.* (1987)
	1.17	0.6 – 1.6	England	Conceiçao *et al.* (1989)
	1.1	0.9 – 1.2	England	Wathes *et al.* (1997)
	1.1	1.05 – 1.14	England – Netherlands	Takai *et al.* (1998)
	0.5	0.42 – 0.63	Denmark - Germany	
	-	1.4 – 1.9	The Netherlands	Ellen *et al.* (2000)
	-	0.1 – 0.3	U.S.A.	Redwine *et al.* (2002)
	0.058	0.032 – 0.091	U.S.A.	Vissier *et al.* (2006)

Health adverse effects caused by dust are related for the most part to respiratory problems such as chronic bronchitis, allergic reactions and asthma-like symptoms (Iversen *et al.*, 2000). Occupational dust concentration thresholds for human health are 10 and 4 mg·m^{-3} of inhalable and respirable dust, respectively, on an 8-hour average, while for short term exposure (15 minutes) 20 mg·m^{-3} is the limit value (HSE, 2007).

The same adverse effects occur in animals, but lower values are recommended as a result of their continued presence in the polluted environment. The maximum recommended concentrations are 3.4 and 1.7 mg·m^{-3} of inhalable and respirable dust, respectively (CIGR, 1992). Adverse effects are noted mainly the respiratory system, yet other factors such as ammonia or pathogens also reduce both animal welfare and the productivity of the farm (Al Homidan *et al.*, 2003; Collins and Algers, 1986).

Environmental dust concentration limits are established according to the EU Directive 1999/30/EC. The daily average PM_{10} concentration limit is 10 μg·m^{-3}, and yearly average concentration must decrease from 40 μg·m^{-3} in 2005 to 20 μg·m^{-3} in 2010. Environmental dust causes reduced visibility and vegetation stress, and contributes to asthma and other respiratory diseases in the population (Grantz *et al.*, 2003).

6.1.3. Animal activity and carbon dioxide production

Carbon dioxide production depends on animal weight and is strongly affected by the variations in animal activity, because it is produced mainly in the respiration process of the animals. The production of other gases such as ammonia, methane and nitrous oxide is initially affected by animal activity in a more complex and less defined manner, since these gases are mainly emitted from manure.

The relation between carbon dioxide and animal weight has been recently used as a way to indirectly determine ventilation flows in naturally-ventilated animal buildings, in the form of a carbon dioxide balance, as it will be explained in this section. This method was first proposed by the German Code (DIN 18910, in 1974), which proposed Equation 6.1 to estimate ventilation flows by measuring carbon dioxide concentrations (Hörnig *et al.*, 2002):

$$V_{CO_2} = \frac{m_{CO_2}}{\Delta C} = \frac{3.0153 \cdot LW^{0.7676}}{C_{inlet} - C_{outlet}} \qquad \textit{(Equation 6.1)}$$

Where:

V_{CO_2}: Ventilation flow calculated from CO_2 balance (m^3·h^{-1})

m_{CO_2}: Carbon dioxide emission rate (mg·h^{-1})

LW: Live weight in the building (kg)

C_{inlet}: Indoor CO_2 concentration (mg·m^{-3})

C_{outlet}: Outdoor CO_2 concentration (mg·m^{-3})

This equation is, however, incomplete because it does not take into account either the influence of the ambient temperature or the animal activity in the respiratory rate, and it seems to underestimate the real carbon dioxide release by animals (Van Ouwerkerk and Pedersen, 1994).

The basis of the current model to apply the carbon dioxide balance was proposed by Van Ouwerkerk and Pedersen (1994), who calculated gas exchange in cattle and pig production according to the metabolic reactions, and quantified the carbon dioxide production as a function of the heat production of the animals expressed in watts. They proposed a carbon dioxide production between 0.17 and 0.20 $L \cdot h^{-1} \cdot W^{-1}$ and considered that 4% of all CO_2 production was produced by manure. This methodology has been further developed for other species (CIGR, 2002; Pedersen *et al.*, 1998), taking into account temperature changes, animal activity and a carbon dioxide production rate of 0.185 $L \cdot h^{-1} \cdot W^{-1}$.

The CO_2 balance method proposed by the International Commission of Agricultural Engineering (CIGR) consisted of three main steps (CIGR, 2002). First, the heat production of the animals must be calculated. Second, the influence of ambient temperature and animal activity must be considered. And third, the ventilation flow is calculated according to measured CO_2 concentrations and the average CO_2 production rate (0.185 $L \cdot h^{-1} \cdot W^{-1}$).

Total heat production of one broiler at 20ºC (ϕ_{tot}) expressed in watts is calculated according to Equation 6.2, where *LW* is the live weight expressed in kilograms.

$$\phi_{tot} = 10.62 \cdot LW^{0.75} \qquad \textit{(Equation 6.2)}$$

Total heat production at temperatures other than 20ºC (Φ^{*}_{tot},) can be calculated according to Equation 6.3, where *T* is the temperature in ºC.

$$\phi^{*}_{tot} = \phi_{tot} + 0.020 \cdot \phi_{tot} \cdot (20 - T) \qquad \textit{(Equation 6.3)}$$

According to CIGR (2002), ventilation flow (V_{CO2}) expressed in cubic meters per animal and hour on a 24-hour basis can be calculated by means of Equation 6.4.

$$V_{CO_2} = \frac{0.185 \cdot \phi_{tot}^{*}}{\left(CO_{2outlet} - CO_{2inlet}\right) \cdot 10^{-6}} \qquad \text{(Equation 6.4)}$$

Where CO_2 concentrations are expressed in parts per million. However, the CO_2 production varies during the day given the changes in animal activity. For that reason, when the balance is performed on an hourly basis, it must be adjusted for animal activity, using a correction factor F_A, which is a unit-less function representing the relative daily variation of animal activity, according to Equation 6.5.

$$V_{CO_2} = \frac{0.185 \cdot \phi_{tot}^{*} \cdot F_A}{\left(CO_{2ind} - CO_{2out}\right) \cdot 10^{-6}} \qquad \text{(Equation 6.5)}$$

Although two sinusoidal models have been contrasted to approximate daily variation of activity in pigs (Blanes and Pedersen, 2005), no model has been proposed for broilers given the high dependence on the lighting programme and management, as it is shown in **Figure 6.1**.

The carbon dioxide balance method has been successfully applied in pig production. Van Ouwerkerk and Pedersen (1994) calculated daily mean estimates of air flow with ±15% precision. Better correlations between measured and modelled ventilation flow can be obtained when animal activity is expressly measured (Blanes and Pedersen, 2005; Sousa and Pedersen, 2004).

When calculating ventilation in poultry farms, the carbon dioxide balance is necessary if direct measurements of ventilation flow are not possible (Gates *et al.*, 2006). Hörnig *et al.* (2002) used the German DIN 18910 (1992 Edition) to calculate ventilation flows so as to estimate the influence of an additive on ammonia emissions. Formosa (2005) compared direct measurement of ventilation flows with tracer gas methods (CO_2 and SF_6) in two commercial broiler farms, one naturally ventilated and one with mechanical ventilation. However, he found some limitations when high ventilation flows occurred, and his calculations did not consider animal activity variations during the day. Finally, Xin *et al.* (2006) tested the CO_2 balance method against an exhaustive direct ventilation flow measurement and found no differences between the two methods if integration times of 30 minutes or longer were used. They also estimated carbon dioxide from litter in about 7% of total CO_2 production.

6.1.4. Objectives

The objectives of this research were: (1) to measure concentrations and emissions of gases (NH_3, CO_2, CH_4 and N_2O) and dust in an experimental farm; (2) to obtain a numerical relationship between animal activity and dust concentration; and (3) to conduct a carbon dioxide balance considering the daily variations in animal activity.

6.2. Materials and Methods

6.2.1. Experiment layout

The experiment was conducted in an experimental broiler facility in the Research Centre for Animal Production and Technology (FOSVWE) in Vechta (Germany, 52º43'07"N; 8º17'42"W, 40 m above sea level), during November and December 2006. 158 male and female Ross broiler chickens were kept in twelve 2 m^2 straw bedded pens, distributed in a 6x8 m room until age of 35 days. **Figure 6.2** shows the arrangement of the pens, together with the measurement devices described afterwards.

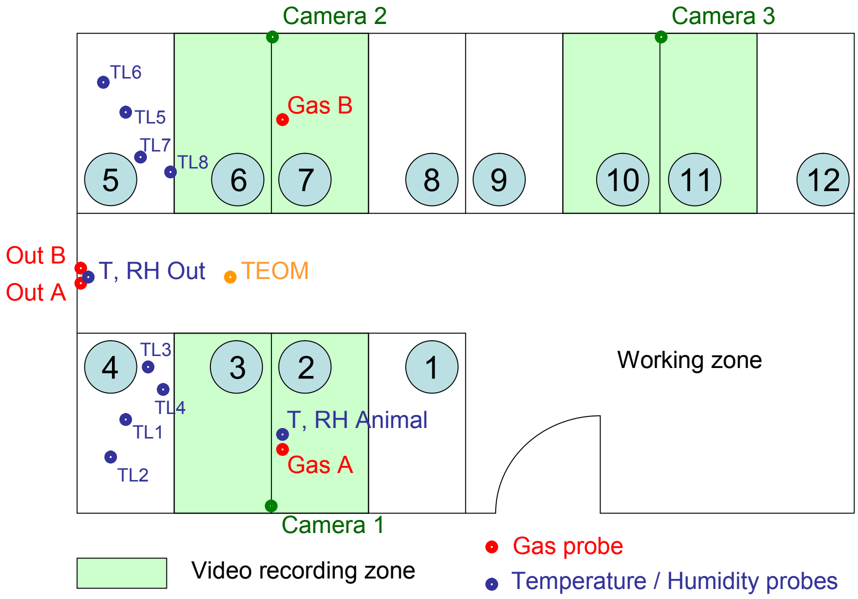

Figure 6.2*. Experimental design, including the distribution of the pens, the monitoring of animal activity and the measurement points for temperature, relative humidity and gas and dust concentrations*

Each pen had a manual feeder and two nipple drinkers, as shown in **Figure 6.3**. Animal weight and feed consumption were determined weekly; litter weight and composition (dry matter, pH, total nitrogen, NO_3^- and total carbon) were also determined at the end of the cycle. The birds had a very fast growth rate, and they reached 2.17 kg at slaughter (day 35) with a total consumption of 3.24 kg of feedstuff each bird (global conversion index of 1.53).

Temperature and relative humidity were adjusted to animal requirements (Avigen, 2002), and a three-level constant ventilation system was used. The light regime consisted of two dark periods during the day. During the first ten days, the dark periods were from 23:00 to 05:00 and from 11:30 to 15:30, whereas during the rest of the rearing experiment dark periods were from 21:00 to 05:00 and from 11:30 to 15:30.

Figure 6.3. *View of two consecutive pens on day 24 of the fattening period*

6.2.2. Measuring animal activity

Six pens were continuously monitored and video-recorded to determine animal activity using three infra-red sensitive cameras located as shown in **Figure 6.2**.

Three infrared lights were used for monitoring night activity. Each of these six pens housed 13 animals during the entire experiment, incorporating one animal from the non-monitored cages when any animal in a target pen died. The video signal was processed using a quad unit (Panasonic WJ-420) and stored in video tapes using a video recorder (Panasonic AG-6040 E) in a room next to the experimental room (**Figure 6.4**).

Figure 6.4. *Video recording system and FTIR multi-gas analyzer*

The assessment of animal activity was carried out on the recorded films every other day until day 25 and then every day until the end of the cycle. The observations were performed in one photogram every 15 minutes for the six pens, so more than 12,000 observations were made during the experiment. Six activities were identified: lying, standing, moving (walking or running), drinking, eating and scratching. For each observation, the number of animals performing each activity was counted, and the percentage of occurrence of each activity was calculated.

An activity index (*Ai*) was defined as the proportion of active birds (*i.e.* birds not lying down). The difference in the activity index between light and dark periods was highlighted according to the following model, evaluated with the General Linear Model Procedure (*PROC GLM*) of SAS System® (SAS, 2001).

$$Ai_i = \mu_i + Light_i + \varepsilon_i \qquad \textit{(Equation 6.6)}$$

Where μ_i is the general mean and $Light_i$ was a bivariate function with values 0 (lights off) and 1 (lights on).

6.2.3. Measuring air pollutants

Gas concentrations (ammonia, carbon dioxide, methane and nitrous oxide) were determined every 30 minutes using a FTIR analyzer (ThermoNicolet 470 ED) placed next to the video monitoring system (**Figure 6.4**). Eight different points were simultaneously measured using a pneumatic multiplexing system: two points were located at the outlet air, and the six remaining points were placed at three different heights (0.5, 1.0 and 1.5 m) in two locations (A and B) as shown in **Figure 6.2**. Total gas emissions and their related uncertainties were calculated as described in chapters 2, 3 and 5.

Dust concentration (PM_{10}) was determined using a TEOM Series 1400 ambient particulate monitor (Rupprecht & Pataschnik, **Figure 6.5**). The measuring system was located at a height of 1 m in the middle of the room as shown in **Figure 6.2**. Measurements were taken every 15 minutes during the entire cycle.

Figure 6.5. *Particulate matter sampling device for PM_{10} (TEOM)*

6.2.4. Environmental conditions

Air temperature and relative humidity at air exhaust and at animal height were measured using temperature and humidity sensors (Hydroclip, Rotronics) and continuously recorded in a data logger (Mikromec-multisens, Technetics). Furthermore, litter temperature was also recorded in cages 4 and 5 (see **Figure 6.2**). Ventilation flow was tested by means of a fan-wheel anemometer (MiniAir6/S6Mik20, Schiltknecht).

6.2.5. Animal activity and dust concentration

The variation in the PM_{10} concentration during the cycle in relation to animal weight and animal activity was evaluated by means of a regression model depending on live weight and animal activity, as follows:

$$PM_{10\,ij} = \beta_1 \cdot LW_i + \beta_2 \cdot LW_i \cdot Light_j + \varepsilon_{ij} \qquad \text{(Equation 6.7)}$$

Where the dependent variable PM_{10} is the measured dust concentration expressed in $\mu g \cdot m^{-3}$ and the independent variables *LW* and *Light* are the average weight of the birds and the light status previously described, respectively. A linear relationship was proposed following the findings of Hinz and Linke (1998). The intercept was considered to be zero, since no dust is expected to be produced when $LW = 0$. ε_{ij} is the model error, and the regression parameters β_1 and β_2 as defined in this equation have the following interpretation: β_1 is the dust concentration per kilogram of animal weight when lights are off, whereas $(\beta_1 + \beta_2)$ corresponds to the dust concentration per kilogram of animal weight when lights are on.

However, the lighting programme used in this study is not usual in commercial farms. For this reason, a similar regression model was adjusted in order to include the effect of animal activity:

$$PM_{10\ ij} = \beta_3 \cdot LW_i + \beta_4 \cdot LW_i \cdot Ai_j + \varepsilon_{ij} \qquad \textit{(Equation 6.8)}$$

Where *Ai* is the activity index previously described. In this case, the regression coefficients take on the following meanings: β_3 is the increase in dust concentration per kilogram of animal weight when all animals are inactive (basal dust concentration), and β_4 quantifies the increase in the basal dust concentration given the proportion of active birds.

Both regression models were made with the *PROC REG* of SAS System® (SAS, 2001), and were adjusted with values on a 15-minutes basis during the entire experiment.

6.2.6. The carbon dioxide balance

The carbon dioxide balance method for estimating ventilation flows was evaluated as follows. Combining Equations 6.2 to 6.5, we obtained the following expression relating the estimated ventilation flow ($m^3 \cdot animal^{-1} \cdot h^{-1}$) and all input variables.

$$V_{CO_2} = \frac{10.62 \cdot LW^{0.75} \cdot \left[1 + 0.02 \cdot (20 - T)\right] \cdot 0.185 \cdot F_A}{\Delta CO_2 \cdot (1 - F_{litter}) \cdot 10^{-6}} \qquad \textit{(Equation 6.9)}$$

In this expression the variable F_{litter} accounts for the proportion of CO_2 produced by litter. This variable was estimated considering the average proportion of CO_2 production during the first 24 hours after slaughter, in relation to the last four days of the rearing period, according to Xin *et al.* (2006) and assuming that CO_2 production from litter was constant within these days.

The different variables were assigned to explicit values in Equation 6.9 as follows.

$$V_{CO_2} = \frac{F_E \cdot LW^{0.75} \cdot F_T \cdot F_{CO_2} \cdot F_A}{\Delta CO_2 \cdot \left(1 - F_{litter}\right) \cdot 10^{-6}} \qquad \textit{(Equation 6.10)}$$

Where F_E is the heat production factor (watts per kilogram of metabolic weight); F_T is the dimensionless correction factor for temperature (see Equation 6.3) and F_{CO2} is the carbon dioxide production expressed in litres per watt. Finally, F_{litter} and F_A have been previously described as the proportion of carbon dioxide produced by litter and the daily relative variation in animal activity, respectively.

Ideally, the model gives similar values for measured and estimated ventilation flows, and thus:

$$V_{CO_2} = V_{measured} \qquad \textit{(Equation 6.11)}$$

Therefore, we can compare the different measured values of ventilation flow with the measured parameters. In Equation 6.10 all directly measured values and the correction for temperature were grouped in the left part of the following expression.

$$V_{measured} \cdot \Delta CO_2 \cdot \frac{\left(1 - F_{litter}\right)}{F_T} \cdot F_A \cdot 10^{-6} = F_E \cdot F_{CO_2} \cdot LW^{0.75} \qquad \textit{(Equation 6.12)}$$

The left part of Equation 6.12 refers the measured carbon dioxide production by animals (E_{CO2}) expressed in litres per animal and hour:

$$E_{CO_2} = V_{measured} \cdot \Delta CO_2 \cdot \frac{\left(1 - F_{litter}\right)}{F_T} \cdot F_A \cdot 10^{-6} \qquad \textit{(Equation 6.13)}$$

On the other hand, in the right part of Equation 6.12 are grouped to obtain an unknown coefficient which can be evaluated with the following regression model.

$$E_{CO_2 i} = \alpha \cdot LW_i^{0.75} + \varepsilon_i \qquad \textit{(Equation 6.14)}$$

Where α is the regression parameter and ε_i is the model error. This model was evaluated with average daily values using the *PROC NLIN* of SAS System® (SAS, 2001). Using daily averages, the correction for animal activity F_A is not, by definition necessary.

To assess the influence of animal activity, two regression models were tested, using average values every 30 minutes during the experiment. The first model (Equation 6.15) considers two independent variables: the metabolic weight ($LW^{0.75}$) and the lighting status (*Light*) defining carbon dioxide production (E_{CO2}), in a manner similar to the model for PM_{10} concentration (Equation 6.7).

$$E_{CO_2 ij} = \beta_1 \cdot LW_i^{0.75} + \beta_2 \cdot LW_i^{0.75} \cdot Light_j + \varepsilon_{ij} \qquad \textit{(Equation 6.15)}$$

The second model (Equation 6.16) considers the influence of animal activity defined by the *Ai* previously described. The objective of this second approach was to obtain a numerical approximation of the influence of animal activity on the production of carbon dioxide.

$$E_{CO_2 ij} = \beta_3 \cdot LW_i^{0.75} + \beta_4 \cdot LW_i^{0.75} \cdot Ai_j + \varepsilon_{ij} \qquad \textit{(Equation 6.16)}$$

6.3. Results

6.3.1. Animal activity

The average percentage of birds performing each activity is shown in **Figure 6.6**. During the dark period, lying was the most frequently performed activity, although other activities (particularly eating) occurred sporadically. During the light period, the initial minutes are usually devoted to eating, and during the whole light period, lying is, on average, performed by only 40% of the birds. The other activities involve mostly scratching, drinking and eating. Walking is the least frequent activity, although it may affect considerably gas and dust emissions.

The activity index, as defined in section 6.2.2, was on average 0.556 and 0.084 for light and dark periods, respectively (global average 0.344), and the differences between the two groups were statistically significant ($P<0.001$). This confirms the assumption of clearly differentiated activity level between dark and light periods.

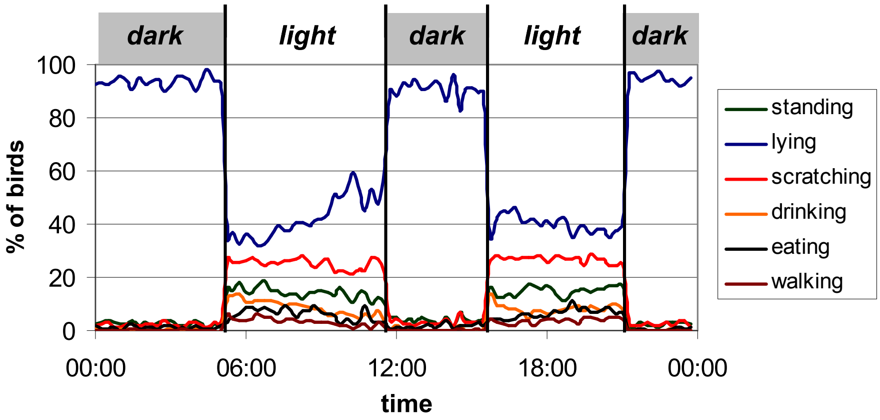

Figure 6.6. *Percentage of birds performing each activity, as affected by light, averaged from day 20 to the day 34 of the cycle*

6.3.2. Dust concentration and animal activity

Dust concentration showed a pattern clearly related to the lighting programme, arising from the clear difference in animal activity levels between light and dark periods. The relation between light and dark dust concentrations was approximately 4:1 for the whole experiment. An increase in dust concentration in relation to animal age was also found, as **Figure 6.7** shows.

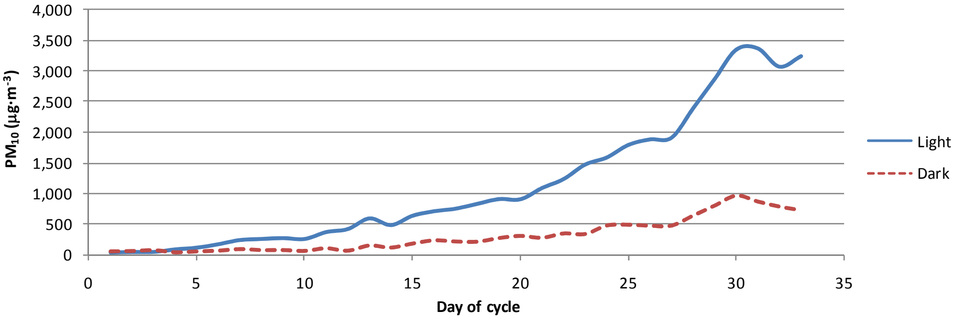

Figure 6.7. *Evolution of daily average PM_{10} concentration during the light and dark periods, as affected by bird age*

Average daily dust concentration was always under 1 mg·m^{-3} in dark periods, and showed values lower than 0.5 mg·m^{-3} for most of the period. Dust concentration during the light period was lower than 1 mg·m^{-3} until day 20 of the cycle, when there was a major increase, probably related with the increase in animal weight. At the end of the cycle (days 30 to 35) average daily dust concentration was over 3 mg·m^{-3}. This is in accordance to what Takai *et al.* (1998) found in Germany, but it is lower than the maximum inspirable dust values reported in other sources (see ***Table 6.1***). However, the ranges of measured inspirable dust reported in the literature are extreme, given the diverse factors affecting this parameter.

A very good linear relationship was found between dust production and animal weight, considering the cross effect of the light status (Equation 6.17 and **Figure 6.8**). The same relationship was previously reported in the literature, and it was attributed to the increased animal activity (Hinz and Linke, 1998; Lacey *et al.*, 2003; Redwine *et al.*, 2002). However, Yoder and Van Wicklen (1988) found a logarithmic relationship between respirable aerosol concentration (RAC) and animal weight; the differences in the type of relationship are probably due to the fact that younger animals were used in the study described here.

$$PM_{10} = 400 \cdot LW + 1091 \cdot LW \cdot Light \qquad \left(R^2=0.88\right) \qquad \textit{(Equation 6.17)}$$

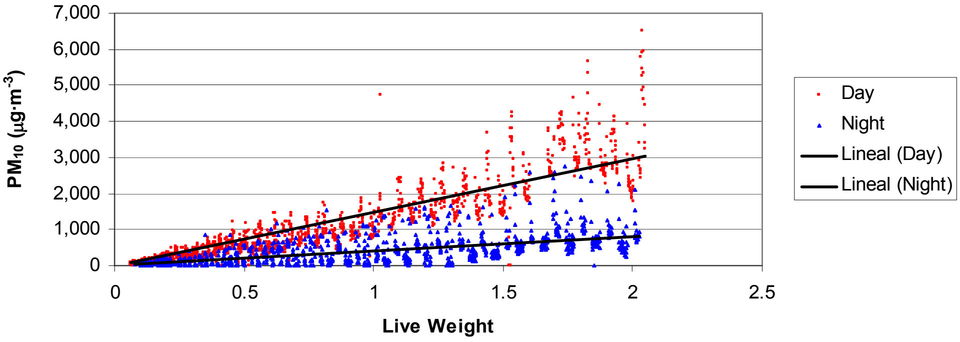

Figure 6.8. *Increase in average PM₁₀ concentration during the light and dark periods, in relation to animal weight*

In relation to animal activity, weekly 15-minute averages of dust concentrations were compared in the present study to the corresponding mean animal activity index (*Ai*), the results of this comparison being shown in **Figure 6.9**.

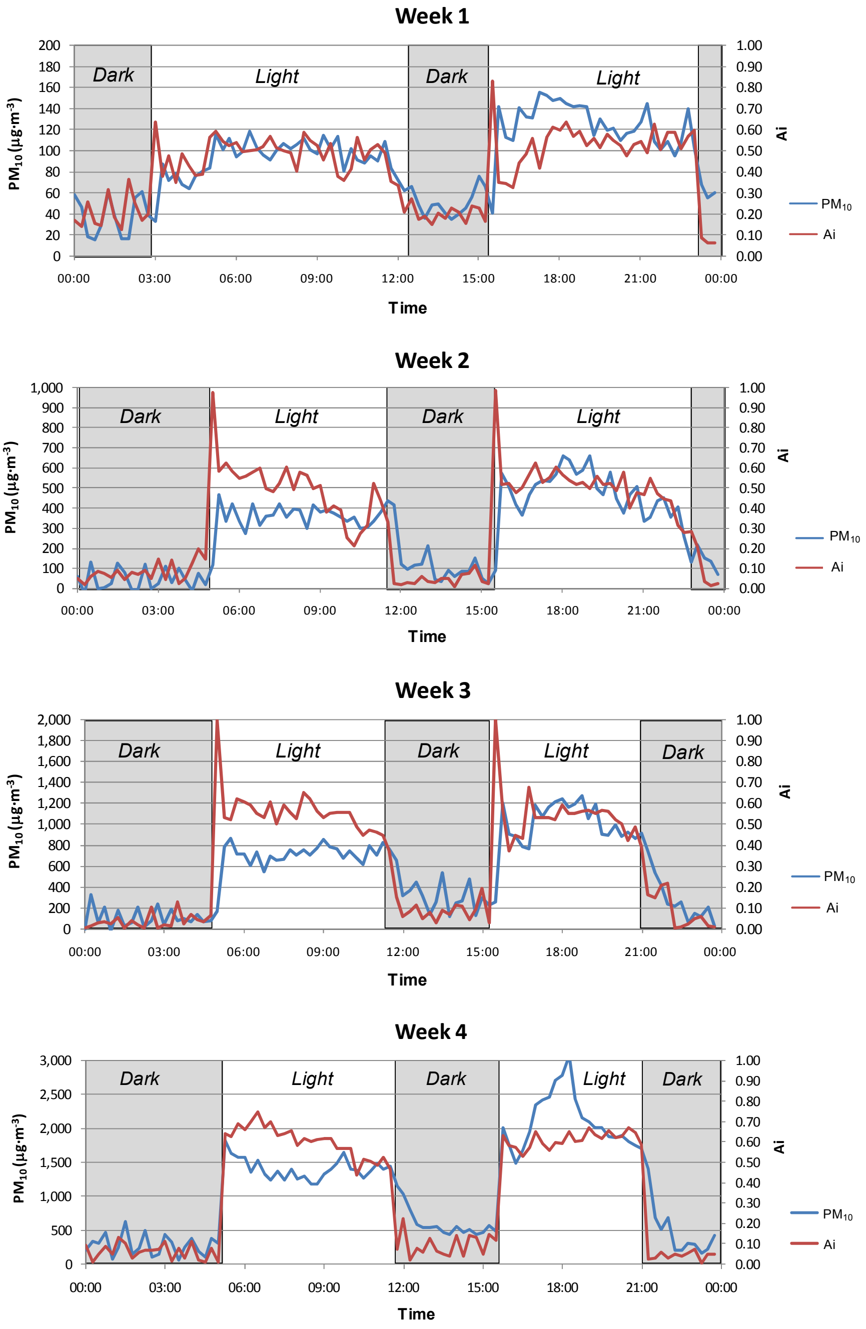

Figure 6.9. *Relationship between lighting programme, dust concentration and animal activity expressed as weekly averages.*

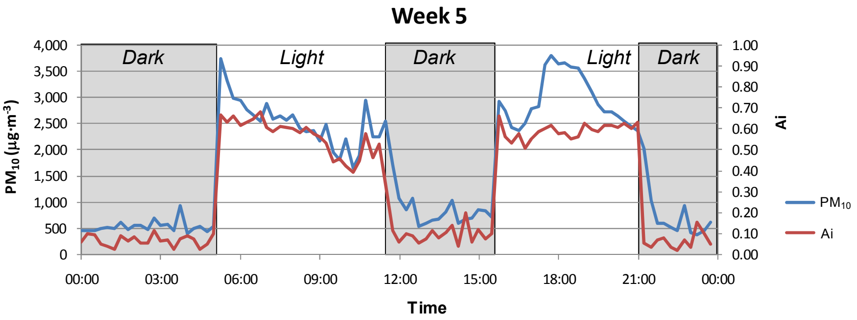

Figure 6.9 (continued). *Relationship between lighting programme, dust concentration and animal activity expressed as weekly averages.*

Although weekly averages are reported, extremely accurate relationships between the two curves are obvious. Minor changes in animal activity are always followed by a change in dust concentration. Thus, there is a strong correlation between dust concentration, animal weight and activity index:

$$PM_{10} = 300 \cdot LW + 2026 \cdot LW \cdot Ai \qquad \left(R^2 = 0.89\right) \qquad \textit{(Equation 6.18)}$$

This equation is almost equivalent to Equation 6.17 if mean values of *Ai* are selected for dark and light periods, respectively. Furthermore, it implies a linear interaction between animal weight and the proportion of active birds.

6.3.3. Gas concentrations and animal activity

Ammonia concentration was lower than 5 mg·m^{-3} until day 28 of the rearing period, but in this moment it increased sharply until about 20 mg·m^{-3} from days 30 to 35. Methane and nitrous oxide concentrations were near the threshold of the measuring device: no increase in nitrous oxide was found during the whole cycle, whereas a very slight increase in methane was found at the end of the rearing period.

Carbon dioxide concentration increased progressively during the cycle, from about 2,000 to 8,000 mg·m^{-3}. The relationship among CO_2 concentration, animal activity and the light regime will be analysed in the next section, and related with the estimation of ventilation flows using the carbon dioxide balance. The evolution in concentrations of NH_3, N_2O, CO_2 and CH_4 is shown in **Figure 6.10**.

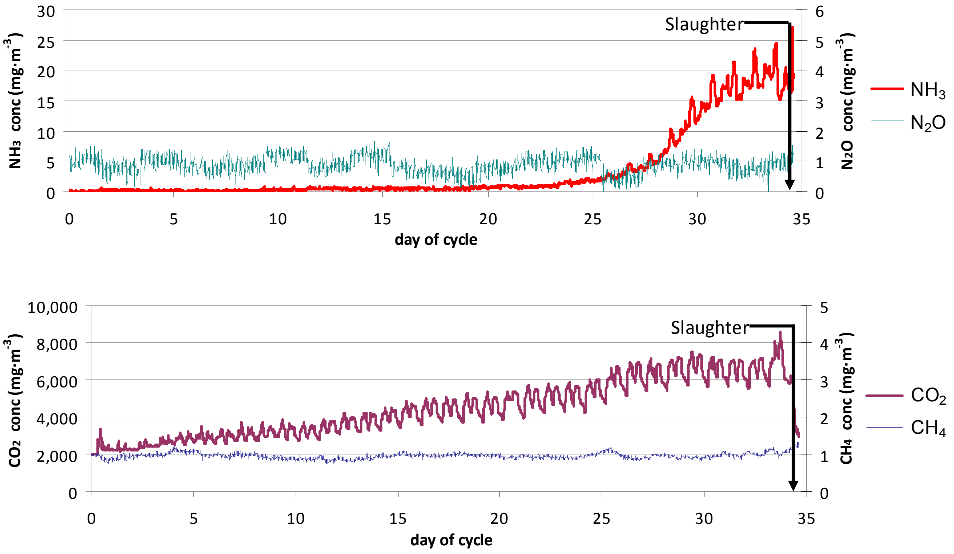

Figure 6.10. *Evolution of the gas concentrations during the rearing period*

For carbon dioxide and ammonia concentrations, daily variations were related to animal activity index *Ai* (**Figure 6.11**). Carbon dioxide is directly related to animal activity, since a part of the energy consumed by animals (and therefore carbon dioxide production) is used for movements.

A basal carbon dioxide production can be assigned to the animals during the dark periods, related to the necessary energy for maintenance.

In the case of ammonia emissions, the relationship is not so clear, because it does not directly depend on metabolic reactions, but rather indirectly on the volatilization processes from the litter: the animals can act as a barrier to the volatilization, or can enhance it by pecking, moving or scratching. No relationship was found between activity and methane or nitrous oxide concentrations, since there was no daily variation in these gases.

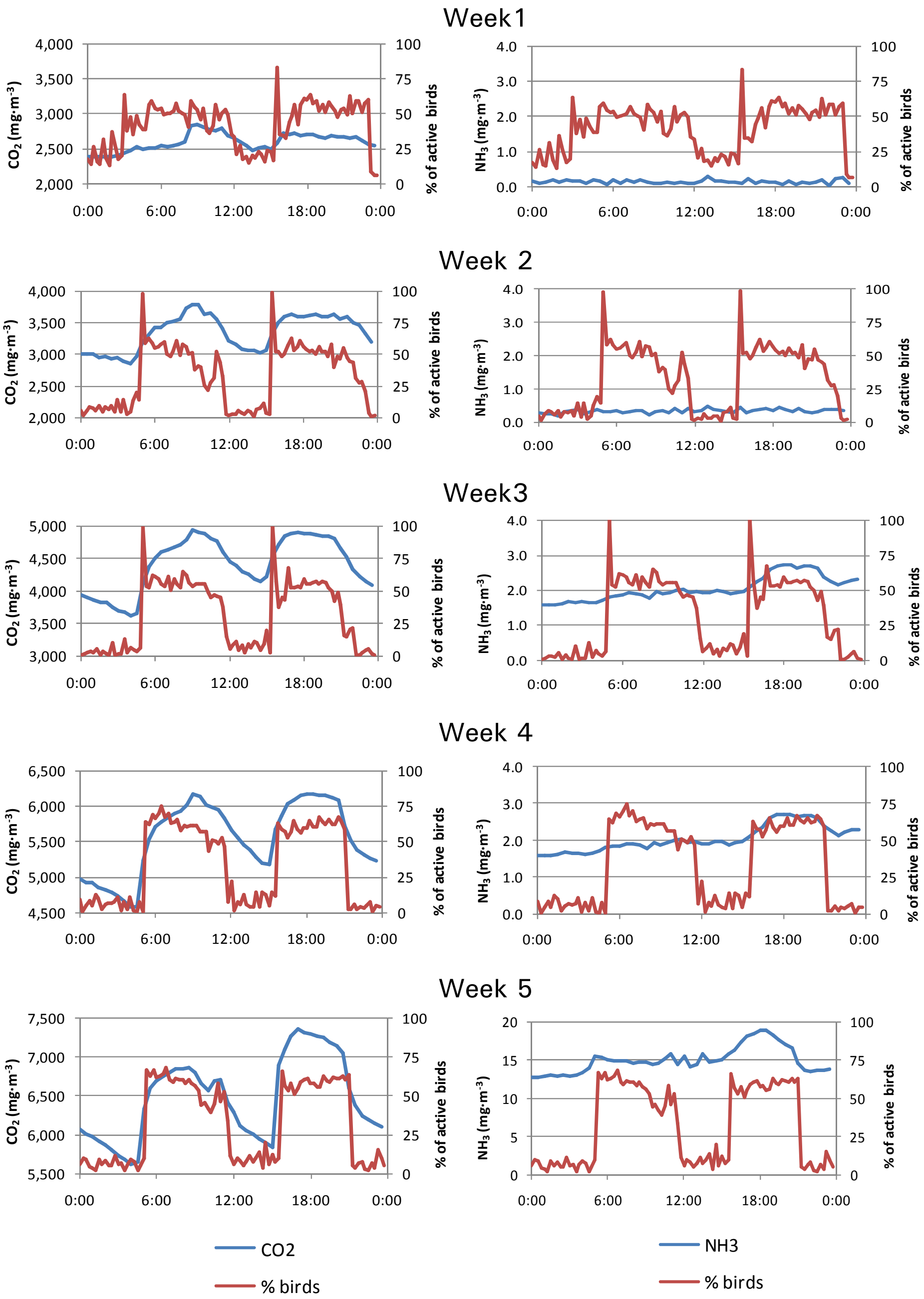

Figure 6.11. Daily variation in gas concentrations (CO2 and NH3) and animal activity expressed as weekly averages

6.3.4. Gas emissions

Figure 6.12 shows the evolution of the accumulated CO_2 and NH_3 emissions. A steep increase in ammonia emissions occurs at the end of the cycle, according to the progressively increasing excreta and to the sudden onset of the decomposition reactions in the litter. Carbon dioxide emissions increase almost proportionally to the metabolic weight of the animals, whereas nitrous oxide and methane emissions were almost negligible.

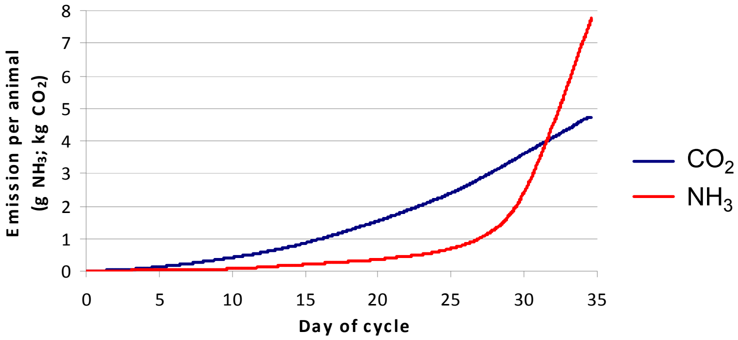

***Figure 6.12.** Accumulated carbon dioxide and ammonia emission*

The final values, together with the estimated uncertainty, are shown in **Table 6.2**. For methane and nitrous oxide, the 95% confidence interval contains the zero, and thus the respective emissions in this experiment are below the detection threshold of the methodology used here.

***Table 6.2.** Average measured gas emissions and estimated uncertainties*

	g·animal^{-1}			
	NH_3	CO_2	CH_4	N_2O
Mean	7.79	4,741	-0.09	0.02
U	*0.60*	*476*	*0.10*	*0.02*
95% CI	*6.62 – 8.97*	*3,810 – 5,673*	*-0.30 – 0.09*	*-0.01 – 0.06*
	g·NH_3 kg meat produced^{-1}			
	NH_3	CO_2	CH_4	N_2O
Mean	3.66	2,234	-0.04	0.01
U	0.34	252	0.06	0.008
95% CI	*3.04 – 4.38*	*1,758 – 2,746*	*-0.16 – 0.08*	*-0.004 – 0.026*

Comparing these results with those obtained in chapter 5, the emission of ammonia is lower in this study in terms of grams of ammonia per kilogram of meat produced. However, if we compare emission curves in both studies (**Figure 5.4** and **Figure 6.12**), the accumulated gas emissions on day 35 are similar. The difference in chapter 6 is that the cycle is much shorter, and the animals had a very fast growth rate. Therefore a better conversion index is achieved, which in turn implies a lower loss of nitrogen. For that reason, the shortening of the growing period is a real option to reduce ammonia emissions from broiler production.

Carbon dioxide emission, however, was higher than the results obtained in chapter 5, probably because the animals in this experiment grew considerably fast and their metabolic activity was very high.

6.3.5. The carbon dioxide balance

6.3.5.1. General adaption of the method

The relation between the mean carbon dioxide production before and after slaughter was obtained from the carbon dioxide production curve (**Figure 6.13**). Before slaughter (days 30 to 33), average carbon dioxide production was 6.81 litres per animal and hour, originated both from animals and litter; during the first 24 hours after slaughter, average carbon dioxide production was 1.36 litres per animal and hour, but in this case the litter was the only source.

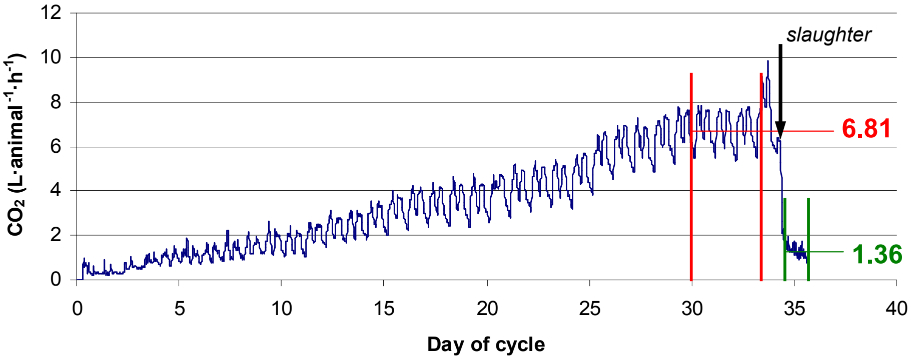

Figure 6.13. *Evolution of the carbon dioxide production and estimation of average productions before and after slaughter*

Assuming that no change in carbon dioxide production from litter existed between these two estimations, it can be concluded that 20% of the total carbon dioxide was produced by the litter (F_{litter} = 0.2). This value contrasts with the lower percentages reported in the literature. Van Ouwerkerk and Pedersen (1994) proposed using a 4% in most cases, although they acknowledged that much higher percentages were possible if reactions in the litter occurred. Xin *et al.* (2006) calculated the carbon dioxide from litter as in this study, and reported 7% of CO_2 produced from litter.

A constant percentage of 20% of the total CO_2 production was considered to be originated in the litter. Therefore, the remaining 80% of the total produced was used to compare the carbon dioxide balance against the direct measurement of ventilation flow.

Daily averages of carbon dioxide production are represented against the weight of the animals in **Figure 6.14**. The regression based on Equation 6.14 is represented as well.

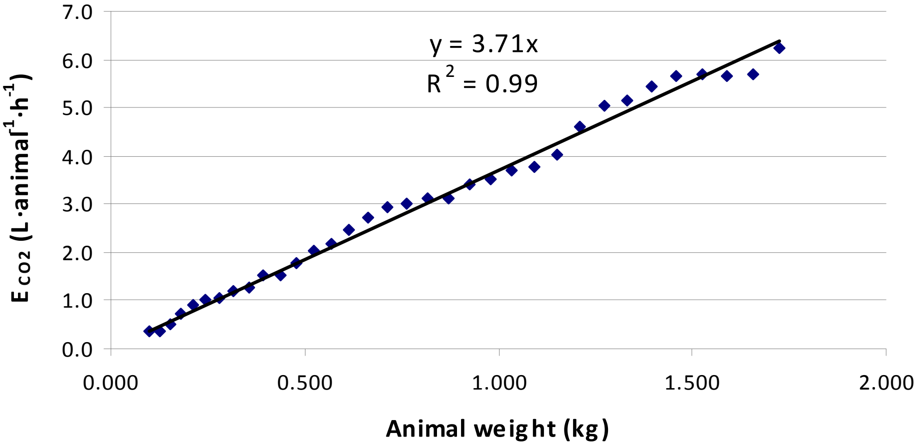

Figure 6.14. *Relation between daily average CO_2 production and animal weight*

In this study, carbon dioxide production was almost proportional to metabolic weight. The estimation of α (3.71) includes the parameters F_E and F_{CO2}. According to the CIGR methodology (CIGR, 2002), a value of 10.62 is proposed for F_E, and 0.185 for F_{CO2}, thus having $\alpha = 1.965$, which is almost half the value obtained in this study. It seems that inaccuracies in the measurements are not enough to explain these differences. However, F_E and F_{CO2} may be higher than those values reported by CIGR (2002). In fact, Blanes and Pedersen (2005) found that F_{CO2} should be 0.201 $L \cdot h^{-1} \cdot W^{-1}$ to obtain a perfect agreement between directly measured ventilation and the estimation of the carbon dioxide balance.

On the other hand, CIGR (2002) acknowledges the evolution in F_E in broilers over the last three decades, given the increased animal growth rates. In this study, the animals grew faster than in most normal conditions (they reached 2.17 kg at day 34), and this could have caused a greater carbon dioxide production. According to the estimation of α (3.71) and assuming that F_{CO2} is 0.201 $L \cdot h^{-1} \cdot W^{-1}$, the F_E estimated in this study is 18.46, which is 74% higher than the value proposed by CIGR (2002). This disagreement is still large enough to consider further studies to determine F_E. **Table 6.3** compares the results of the present study with the CIGR values.

Table 6.3. *Values of F_E and F_{CO2} comparing this study with the CIGR*

Method	F_E ($W \cdot kg^{-0.75}$)	F_{CO2} ($L \cdot h^{-1} W^{-1}$)	$\alpha = F_E \cdot F_{CO2}$
CIGR (2002)	10.62	0.185	1.96
This study	18.46	0.201	3.71

6.3.5.2. The influence of animal activity

For the 30-minute performance of the carbon dioxide balance, changes in the light status (and thus in the animal activity) had a significant influence on CO_2 production. The inclusion of the light status in the regression model to estimate the carbon dioxide production resulted in Equation 6.19.

$$E_{CO_2} = 3.15 \cdot LW^{0.75} + 0.737 \cdot LW^{0.75} \cdot Light \qquad \left(R^2=0.99\right) \quad \textit{(Equation 6.19)}$$

The influence of the light programme, however, can not be compared with other situations because it was very specific in this study. For this reason, a regression model relating CO_2 production, animal weight and activity index was proposed:

$$E_{CO_2} = 3.08 \cdot LW^{0.75} + 1.347 \cdot LW^{0.75} \cdot Ai \qquad \left(R^2=0.99\right) \quad \textit{(Equation 6.20)}$$

Equation 6.20 is almost equivalent to Equation 6.19 if mean values of *Ai* are selected for dark and light periods, respectively. Furthermore, it implies a linear interaction between animal weight and the proportion of active birds. The first term of Equation 6.20 represent the tranquil CO_2 exhalation rate (TCER) proposed by Ni *et al.* (1999) for pigs, and the activity of the animals can cause an increase of as much as 44% in the carbon dioxide production depending on the *Ai*.

The carbon dioxide balance was calculated on a 30-minute basis using Equation 6.19 to predict carbon dioxide production from the animals. However, even considering the correction for animal activity, a discrepancy of more than 25% was found in some cases, particularly in the first 10 days of measurements (**Figure 6.15**).

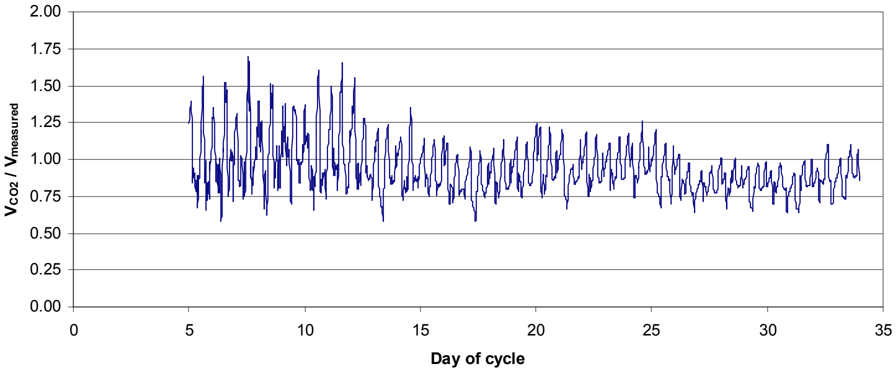

Figure 6.15. *Relation between the calculated ventilation flow according to the carbon dioxide balance (V_{CO2}) and the measured ventilation flow ($V_{measured}$)*

The reason for this discrepancy lies in the change between dark and light periods. For illustration purposes, carbon dioxide production and the activity index during the last four days of the rearing period are shown in **Figure 6.16**. A change in the light status did not involve an immediate change in the carbon dioxide production by animals. In contrast, the change in the carbon dioxide concentration is produced smoothly, particularly when changing from light to darkness.

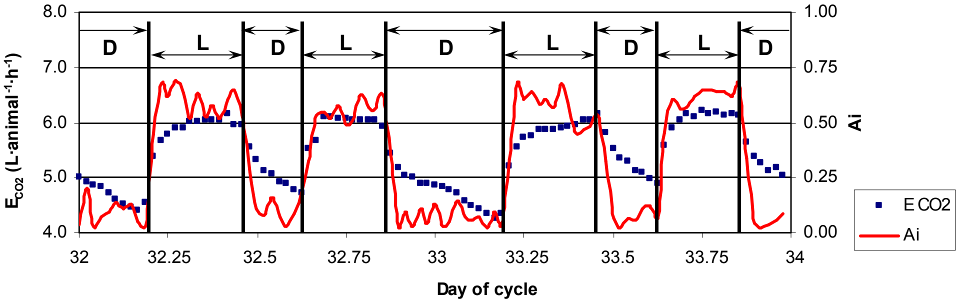

Figure 6.16. *Evolution of the carbon dioxide production and the animal activity index during the days 32 and 33. Light status is indicated (L = Light; D = Dark)*

A possible reason for this progressive change is the fact that carbon dioxide concentrations change according to a decay formula, and therefore cannot change drastically. However, given the ranges of gas concentrations, the ventilation rates and the volume of the building, 99% of the concentration change is produced within the first 20 minutes, and therefore, this smooth change between dark and light periods would not be detectable with a 30-minute measuring interval.

The other reason for this is that when a change in the light occurs, a change in animal activity is perceived, and thus the *Ai* changes. Nevertheless, the metabolic status is not reflected by the observed activity. This is particularly significant in the first hours of sleep. According to Shapiro and Flanigan (1993), there is a transition from wakefulness to sleep, characterised by active brain activity, which could explain the smooth transition in carbon dioxide production by animals. According to these authors, one of the functions of sleep is energy conservation, decreasing the metabolic rate (oxygen consumption, heart rate, body temperature and thus carbon dioxide production) by 5 to 25%.

6.4. Conclusions

An activity index was defined to describe the influence of animal activity on gas and dust production from broilers. There is a strong relationship between the lighting programme, the animal behaviour and the emission of gases and particulate matter. For this reason, lighting determines the daily variation of particulate matter and gas production.

PM_{10} concentration varied linearly with animal weight and during light periods was on average four times higher than during dark periods. Maximum dust concentrations were found at the end of the cycle (3.5 $mg \cdot m^{-3}$ on average during light periods). The effect of animal activity on dust production was quantified with a regression analysis, obtaining a significant cross interaction between animal weight and animal activity ($R^2 = 0.89$).

Ammonia emissions increased drastically from day 25 on and the total amount emitted was 7.79 g $NH_3 \cdot bird^{-1}$.Total carbon dioxide emission during the cycle was 4.71 $kg \cdot bird^{-1}$, whereas methane and nitrous oxide production was negligible.

Average daily carbon dioxide production varied linearly with the metabolic weight of the animals ($R^2 = 0.99$), but the application of the carbon dioxide balance resulted in a higher emission of carbon dioxide than that obtained using the default CIGR data, probably as a consequence of the fast growth rate of the animals during this experiment.

Animal activity, as defined in this study, could not be precisely related to carbon dioxide production. The movements of the animals cannot be directly related to their metabolic activity, particularly during the first hours of the dark periods.

The activity index described in this study is a suitable indicator of PM_{10} production in broilers reared on litter, and further study will aim to relate broiler activity and carbon dioxide production.

6.5. References

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Chapter 7

Conclusions and future work

7.1. Conclusions

The measurement of gases emitted from commercial farm animals represents a technical and methodological challenge, and this is particularly true as evidenced in this thesis. Although techniques described herein have been widely applied to measure gas emissions, many were implemented for the first time for this research under Mediterranean conditions. Indeed, this is an emerging research topic in Spain which will continue to challenge the livestock sector.

In accordance with this challenge, some of the objectives of this thesis focused on the development and implementation of suitable and standardised techniques to measure gas emissions. These techniques have been subjected to experimentation and will be useful for future studies. In terms of methodology, there are three main contributions of this PhD:

(1) A general and documented procedure to analyse the uncertainty of measured emission rates was developed.

The uncertainty analysis allows scientists and engineers to understand and make efficient use of the results of a study. On the other hand, policy makers are able to understand the credibility of the data in order to make sound policy decisions.

This analysis is not only a quantitative estimator of the quality of the reported results, but it also allows for the improvement of the measurement technique, since the impact of each uncertainty source can be quantified. If researchers know exactly where the uncertainty lies, then the efforts can be directed to reducing it so as to produce more reliable findings.

(2) The mass balance method was applied to measure gas emissions from commercial rabbit and broiler farms, and the uncertainty of the measuring system used in this research was characterised.

The imprecision in measuring gas concentrations was identified as the main uncertainty source in single measurements of ventilation rates. However, ventilation flows were identified as the main source in the long-term estimation of emissions.

(3) In order to directly determine hourly ventilation flows, a reliable and user-friendly circuit was designed to register the operation status of the fans in commercial farms. The performance of this circuit was evaluated in terms of economic cost, labour demand and uncertainty in the results.

Once ventilation is precisely established for a particular setting, gas emissions can be readily estimated by measuring gas concentrations. Furthermore, accurate information about ventilation flows makes farm management easier both in terms of energy consumption (fan performance and financial savings) and, what is more important, in terms of welfare of farm animals and workers.

After the methodological aspects were developed, gas emissions in rabbit and broiler farms were measured. In this context, three main conclusions may be highlighted:

(4) Ammonia, carbon dioxide, methane and nitrous oxide concentrations and emissions in rabbit production (fatteners and reproductive does) were systematically measured and recorded in the Mediterranean area of Spain, both in summer and winter conditions.

The results constitute a particularly significant conclusion of this thesis, given the very scarce information on this species. Furthermore, the difference in emissions between summer and winter conditions was also determined.

(5) A nitrogen balance was conducted for an entire rabbit fattening cycle, and all nitrogen inputs and outputs were quantified.

A reliable estimation of nitrogen excretion is essential to use manure more efficiently in the effort to minimise environmental impacts, and it is a crucial input to estimate ammonia and nitrous oxide emissions in the national gas emissions inventories.

(6) Ammonia, carbon dioxide, methane and nitrous oxide concentrations and emissions were measured in a commercial broiler farm in the Mediterranean area of Spain both in summer and winter conditions.

The final results on gas emissions were similar to those obtained in previous studies in other countries, which is natural considering that the indoor environment in this production system is strictly controlled. The dynamics in the emission process were also described and, as in the case of rabbits, the difference between winter and summer conditions was quantified.

Finally, in terms of factors affecting gas and dust production, there are two highly noteworthy conclusions of this PhD:

(7) Dust concentration in broiler production depends linearly on animal live weight and animal activity, which in turn is drastically affected by the lighting programme.

(8) The carbon dioxide balance performed satisfactorily on a 24-hour basis. However, the daily variation in animal activity did not explain the variation in the production of carbon dioxide on a 30-minute basis.

In addition to the significant academic and scientific achievements of this PhD thesis and the resulting conclusions drawn from the studies, the work presented here has contributed decisively to the development the research group *Sistemas y Tecnologías de la Producción Animal (STEPA)* in the area of atmospheric pollution caused by the intensive rearing of livestock. One of the objectives of this research group is to integrate the experimental measurements of gas emissions such as those described herein into the Spanish national gas emissions inventory.

7.2. Future work

As with all research work of this nature, more questions have arisen during the investigation than those initially considered. For this reason additional studies are needed to confirm or refute the results presented and to contribute to improving the scientific knowledge so as to solve practical questions in relation to gas emissions from livestock production. These questions are being addressed in *STEPA's* ongoing studies while others will be considered in upcoming projects.

Although in chapter 2 the approach for the uncertainty analysis was clearly described, a special effort should be made in each specific future study to precisely define the input variables and their related probability distributions, because it is one of the fundamentals of the uncertainty analysis. Preferably, a measuring system should be designed to achieve a measurement precision, depending on the research objectives and the final use of the results

With the measuring system used in this research, ventilation was identified as the main contributor to the overall uncertainty in long-term measurements of emissions. A more precise characterisation of this variable would lead to better estimates of gas emissions. In this context, more accurate techniques to calibrate fans on the farm are now available and are being used in our current studies.

With regard to the gas emissions in rabbit and broiler production, more studies must be conducted in other farms. As stated in chapter 1, the emission factors can be only determined in the long term and considering average conditions. This is a descriptive task to characterise the current emissions, which will lead to a consequent major challenge which was work beyond the scope of this thesis: the identification of management techniques which involve reduced emissions at affordable costs. The reduction of the fattening cycles in broiler production was identified as an ammonia reduction option, but the real consequences of this measure should be fully evaluated.

The results obtained in this thesis can be useful for other EU countries in the Mediterranean area, and even to other non-EU countries having climate and livestock systems similar to those described herein. Furthermore, the research in such a complex area demands international cooperation. Countries in the Mediterranean basin, having similar climate conditions and livestock management systems, should conduct coordinated experiments to obtain more reliable results using common knowledge and techniques, as already done in some northern European countries. Therefore, future work should aim not only to obtain uniform and contrasted results using standardised measuring systems, but also to contribute to global development and the transfer of technology, particularly to developing countries.

Regarding rabbit emissions, a non-usual pattern in the daily emissions of carbon dioxide was obtained, which could be related to the special daily pattern in the activity of these animals. Studies on gas production by animals in climate-controlled chambers, considering their age and the temperature, would give very valuable information about the processes leading to gas production. These studies would be particularly useful to implement the use of the carbon dioxide balances to determine ventilation flows, as well as to quantify the methane produced by the enteric fermentation in this species.

Finally, the activity index proposed in this thesis, in relation to dust and gas emissions from broilers, must be further evaluated for several reasons. On the one hand, the linear relationship between dust and animal activity seems obvious in this study. However, the results were obtained using a specific litter material in an experimental facility, and therefore more studies are needed to confirm the results obtained here. On the other hand, the relation between animal activity and carbon dioxide production must be more clearly defined. Furthermore, as the carbon dioxide balance differed considerably from the procedure recommended by CIGR, future work could be aimed at characterising this variable with more precision.

Despite some reluctant opinions on the ability of humans to change our environment, it has long been demonstrated that our activities can damage it significantly. Livestock production also has a global impact, particularly related to atmospheric pollution: climate change, acidification and eutrophication, especially when intensive facilities are considered. Other questions such as human health and animal well-being are also a growing concern of the livestock sector.

A significant part of this research was justified in terms of the elaboration of national inventories, following the recommendations of the IPCC and other regulations on gas emissions. However, future research in this area should be directed towards obtaining solutions for the general challenges of the 21st century, regardless of political actions. What is more, political actions on the environment, animal welfare and human health in livestock production should be a consequence derived from the scientific findings in these areas.

In conclusion, the measurement of the atmospheric pollutants from animal production and the factors affecting their production is an extensive research area. Research objectives must be established not only to improve the quality of the environment, but also to contribute to maintaining livestock production as a profitable economic activity in our global society.

Published and submitted papers

The following papers have been published, submitted or presented as a direct result of this thesis:

Calvet, S., Cambra-López, M., Estellés, F., Carbonell, F., Ferrer, P. and Torres, A.G. (2006). Ammonia emissions and nitrogen balnce in a broiler farm in Spain in summer conditions. XVI CIGR World Congress – Agricultural Engineering for a Better World. Bonn (Germany).

Calvet, S., Cambra-López, M. and Torres, A.G. (2006). Ventilation measurement systems in mechanically ventilated farms for estimating gas emissions. XVI CIGR World Congress – Agricultural Engineering for a Better World. Bonn (Germany).

Calvet, S., Blumetto, O. and Torres A.G. (2006). Nitrogen balance and ammonia emissions in a rabbit farm in Mediterranean conditions. XVI CIGR World Congress – Agricultural Engineering for a Better World. Bonn (Germany).

Calvet, S., Úbeda, Y., Cambra-López, M., Blanes-Vidal, V. and Torres, A.G. (2007). Experimental results of ammonia emissions from broiler production in Spain. Ammonia Emissions in Agriculture, Proceedings of the International Conference on Ammonia in Agriculture p. 171-172. Wageningen Academic Publishers. Wageningen (The Netherlands).

Calvet, S., Estellés, F., Hermida, B., Cambra-López, M. and Torres, A.G. (2007). Experimental results of ammonia emissions from a fattening rabbit farm in Spain. Ammonia emissions in agriculture, Proceedings of the International Conference on Ammonia in Agriculture. p. 169-170. Wageningen Academic Publishers. Wageningen (The Netherlands).

Calvet, S., Estellés, F., Hermida, B. and Torres, A.G. (2008). Experimental balance to estimate the efficiency in the use of the nitrogen in growing rabbits. Submitted to the *World Rabbit Science* (February 2008).

Calvet, S., Cambra-López, M., Blanes-Vidal, V. and Torres, A.G. (2008). A system for measuring ventilation flows in mechanically-ventilated commercial farms. Submitted to *Applied Engineering in Agriculture* (February 2008).